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COST-EFFECTIVENESS OF FLIGHT SIMULATORS FOR MILITARY TRAINING.

Volume I.

Use and Effectiveness of Flight Simulators.

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(10) Jesse Orlansky
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Volume I:

Use and Effectiveness of Flight Simulators

Jesse Orlansky

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August 1977

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INSTITUTE FOR DEFENSE ANALYSES

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ABSTRACT

Flight simulators cost less to operate than do aircraft; estimates range from 5 to 20 percent. Many studies have shown that skills learned in flight simulators can be performed successfully in aircraft, i.e., the use of flight simulators for training purposes saves flight time. The critical issue is whether the amount of flight time saved by the use of simulators is worth their cost. The cost-effectiveness of flight simulators for training has been demonstrated only in a few recent studies which report that the procurement cost of simulators can be amortized in a few years. Current R&D about flight simulators centers about the need for motion and wide angle visual display systems. Flight simulators have achieved their greatest use by the military so far in undergraduate flight training. Their greatest potential for future savings lies in transition and continuation training which account for the major costs of military flying. Consistent methods of data collection and cost estimating, not now available, are needed to evaluate the cost-effectiveness of alternative flight training programs, including the use of various types of simulators, part-task trainers, new instructional strategies, and the like. The report provides a preliminary cost model which identifies the data needed to develop cost estimates for use in cost-effectiveness analyses of flight training.

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ABBREVIATIONS

ACM	Air Combat Maneuvering
AFR	Air Force Regulation
AIAA	American Institute of Aeronautics and Astronautics, Inc.
ASPT	Advanced Simulator for Pilot Training (previously ASUPT) (Air Force)
ASUPT	Advanced Simulator for Undergraduate Pilot Training (now ASPT) (Air Force)
AWAVS	Aviation Wide Angle Visual System (Navy)
CBO	Congressional Budget Office
CCTS	Combat Crew Training School
CFT	Cockpit Familiarization Trainer
CGI	Computer Generated Imagery
CIG	Computer Image Generation
CNATRA	Chief of Naval Air Training
CNET	Chief of Naval Education and Training
CPT	Cockpit Procedures Trainer
CRT	Cathode Ray Tube
CTEA	Cost and Training Effectiveness Analysis
CTER	Cumulative Transfer Effectiveness Ratio
DOF	Degrees of freedom
DSB	Defense Science Board

DT/OT	Development Test, Operational Test
ECM	Electronic CounterMeasure
EWOT	Electronic Warfare Officer Trainer
FIST	Fire Control Integrated System Trainer (AC-130)
FOV	Field of View
FSAA	Flight Simulator for Advanced Aircraft (NASA)
FSR	Flight Substitute Ratio
GAO	General Accounting Office
IFS	Instrument Flight Simulator
IFT	Instrument Flight Trainer
IP	Instructor Pilot
IPIS	Instrument Pilot Instructor School
IR&D	Independent Research and Development
ITER	Incremental Transfer Effectiveness Ratio
LAMARS	Large Amplitude Multimode Aerospace Research Simulator
NCLT	Night Carrier Landing Trainer
nmi	Nautical Mile(s)
NOE	Nap of the Earth Flight
NTEC	Naval Training Equipment Center
OFT	Operational Flight Trainer
OMB	Office of Management and Budget
PIT	Pilot Instructor School
PM Trade	Program Monitor for Training Devices
RDT&E	Research, Development, Test, and Evaluation
SAAC	Simulator for Air-to-Air Combat (Air Force)

SAC	Strategic Air Command
SEWT	Simulator for Electronic Warfare Training
SFTS	Synthetic Flight Training System (Army)
SIM SPO	Simulator Systems Program Office (Air Force)
TAEG	Training Analysis and Evaluation Group (Navy)
TER	Transfer Effectiveness Ratio
TTB	Tanker Transport Bomber
UNT	Undergraduate Navigator Training
UPT	Undergraduate Pilot Training
VCTS	Variable Cockpit Training System (Coast Guard)

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SUMMARY

A. BACKGROUND

The purpose of this paper is to evaluate research and development concerned with determining the cost and effectiveness of flight simulators for military training.[(1)] Military flying costs were about $2.7B for 6.4M flying hours in FY 1975. Flying hours are being reduced by an amount expected to reach 17 percent in FY 1981. The DoD now spends about $300M per year to procure flight simulators; the total for FY 1975-1979 is estimated to be about $1.5B. If flying costs ($2.7B) are actually reduced by 25 percent ($675M), the procurement cost of these simulators ($1.5B) could be amortized in 2.2 years (excluding simulator operating costs, discount, and other factors). About $28M was allocated for RDT&E on flight simulation in FY 1977.

Flight simulators are said to have the following advantages: they are a convenient means for instructing and observing a pilot; they provide experience with extreme conditions not often encountered in flight, e.g., unusual attitudes, speeds, controllability conditions, and malfunctions, without risks to safety; they provide automatic recording and playback; they allow objective performance measures; they are able to freeze conditions and repeat maneuvers not possible in flight; and, in addition, cost less to operate than aircraft. The disadvantages of simulators are said to be that they may not adequately duplicate all flight conditions and that they cannot, in any case, evoke the motivation and stress provided only by actual flight.

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(1) This paper was prepared under IDA Task T-134, Costing and Effectiveness Methods for Defense Training under the technical cognizance of the Military Assistant for Training and Personnel Technology, Deputy Director Defense Research and Engineering (Research and Advanced Technology).

B. FINDINGS

1. Cost of Training

Hourly operating costs of flight simulators approximate 5 to 20 percent of the hourly operating costs of the aircraft they emulate; the median value is about 12 percent. Although the data on which these estimates are based come from sources that may not be directly comparable, there is no reason to doubt that simulators cost much less to operate than aircraft and that their use could significantly reduce training costs. Whether or not this potential benefit is realized depends on the extent to which skills learned in a simulator carry over (i.e., transfer) to aircraft and save flight time otherwise required for training. Rates of transfer must be sufficiently high to permit the total cost of attaining a given level of flight proficiency using simulators (or some combination of simulators and aircraft) to be less than the total cost incurred by using aircraft alone.

The military services do not appear to have methods useful for estimating costs of new options or of possible changes in current flight training programs. The data systems that exist are generally limited to extracting full costs of given training programs from base accounting systems for the purpose of setting reimbursement rates for interservice and foreign student training. Except in the area of flying-hour costs, there is no attempt in these systems to associate or correlate types and levels of resources consumed with increments of training loads or with particular activities within the training programs. There are large areas of commonality in resource requirements between flight training and other facets of peacetime military operations, (e.g., military pay and allowances, base support personnel and services). In these common areas, the applicable data seem to be available. However, there remain significant resource-consuming activities that are peculiar to the training establishment for which requisite data are not collected

(e.g., cost loadings for instructional personnel, operating and support establishment for training, command structure). A preliminary model emphasizing analyses of cost-tradeoffs between flight and simulation has been developed in Volume II. The model provides a basic structure and identifies the types of data needed to develop parametric estimates of training costs.

2. Effectiveness of Flight Simulators

The effectiveness of flight simulators for training purposes is supported by many studies which show that skills learned in flight simulators can be performed successfully in aircraft; no studies were found which show that simulators are not effective for training. This means that the use of flight simulators saves flight time. This is a consistent finding of studies which extend from 1939 to the present. Positive transfer of training has been demonstrated for almost all types of simulators and aircraft, maneuvers, and skill levels of the pilots. Simulators appear particularly effective for training on tasks where success depends on following precise procedures (e.g., instrument flight, approach, and landing). There are fewer studies on the effectiveness of simulators for training on other aspects of flight (e.g., air-to-ground attack, air-to-air combat), largely because of previous limitations in the capabilities of simulators for these types of training. Most of the studies, but not all, involve undergraduate flight training.

The amount of flight time saved due to training in a flight simulator varies widely for reasons which cannot be discerned from the available studies. Transfer of training (or flight savings) has not always been measured in the same way. Factors believed to influence the amount of transfer include the type of simulator, the tasks for which it is used, the experience level of the pilots and the instructional strategy. Systematic studies would be needed to establish the applications for which the new, advanced simulators are likely to be most effective. Almost no attention has been given to incremental transfer, i.e., the rate of improvement

with additional training, a type of information needed to determine when it becomes more cost-effective to train in aircraft rather than in simulators. Most studies on the effectiveness of flight simulators do not consider cost factors.

The effectiveness of flight simulators can be measured in other ways than by the amount of flight time saved, but this is rarely done systematically and objectively in flight. Examples of other measures of effectiveness are the quality (or precision) of flight performance (after a fixed amount of simulator and/or aircraft time), errors (e.g., failure to adhere to specified procedures, near-accidents and accidents), and pilot acceptance and morale.

3. Cost-Effectiveness of Flight Simulators

The cost-effectiveness of flight simulators has been demonstrated only in a few recent studies. A Navy study concludes that the new P-3C flight simulator, when used for transition training of about 200 Naval pilots a year, saves enough flight time to be amortized in about 2 years. A Coast Guard study concludes that its new simulator, used for transition and proficiency training of about 500 pilots per year for the HH-52A and HH-3F helicopters, can be amortized in about 2 years. Initial results in an ongoing Cost and Training Effectiveness Analysis (CTEA) by the Army suggest that use of the new CH-47 simulator for transition training should save about $8,000 per pilot. An analysis provided by a commercial airline indicates that its simulators can be amortized in less than 9 months and the entire training facility in less than 2 years. The cost-effectiveness of flight simulators claimed in all of these studies appears to have resulted from the introduction of both an advanced simulator and improved instructional procedures. There is no way, in any of these studies, to separate the contribution of the simulator from the contribution of the new way in which it was used.

4. Improvement of Flight Simulators

Advanced flight simulators have only recently become available to the services for use either in experimental or operational studies of training. Major attention has been given to the need for platform motion in new flight simulators. Findings from a series of studies, some of which are still unpublished, indicate that there is no difference in the flight performance of pilots trained in simulators with or without platform motion. The finding appears to hold for inexperienced and experienced pilots, for training on basic flight and on acrobatic maneuvers, and for several types of simulators. The finding is not necessarily universal. It has been observed primarily with undergraduate pilots flying a center-thrust airplane on a simulator with a very wide field of view visual display (but also for a two-engine, i.e., non-center-thrust airplane and on a simulator without a visual display). Different time delays in the motion and visual systems on ASUPT, the simulator used in some of these studies, may have influenced the particular results obtained with that device. The ASUPT motion system is being improved and new tests are scheduled to replicate the initial findings. The findings do not necessarily apply to simulators used for training on multi-engine aircraft (e.g., asymmetric thrust conditions) or at extreme flight conditions where motion cues may prove to be significant. Additional studies of motion are now underway or planned and a more complete understanding of what platform motion contributes to training will soon be available. It is important to sort out the influence of motion cues in simulators due to maneuvering the airplane from those due to turbulence or equipment failure. Some studies will consider the need for other motion cues (e.g., g-suit, g-seat, dynamic shoulder straps) and the relation of motion cues to visual cues (particularly the size of "wide angle" field of view displays). That platform motion tends to improve performance in the simulator has long been known; the fact that simulator motion does not contribute to flight performance is a new, but not unanticipated, finding.

Visual displays are needed in simulators for training in such critical maneuvers as landing, air-to-ground attack, aerial refuelling, and air-to-air combat. Few studies are now being conducted on the contribution that the new visual systems make to training or on the characteristics such systems must have in order to be effective for training or, even if they are effective, whether they are worth their cost. An advanced visual sytem can cost from 5 to 10 times as much as the motion bases now receiving so much attention and up to half the total cost of a modern flight simulator. Although R&D on visual simulation is not being neglected, most of the effort is directed towards the development of equipment rather than towards specifying the perceptual requirements that such equipment should satisfy.

Flight simulators are primarily teaching devices and all advanced simulators have features that can influence instructional strategies. These include objective measurement of pilot performance; cueing mechanisms to facilitate learning, playback, problem freeze; and repeat the automatic demonstration modes. Many plans exist for R&D on the optimum use of these features. Unfortunately, studies on instructional strategies tend now to have a lower priority than studies related to motion.

5. Future Developments

Most R&D on flight simulators is concerned with their use in undergraduate training. However, this type of training accounts for about 10 percent of all variable flying costs while transition and continuation training account for about 80 percent (the remainder is for support flying). (Transition training concerns learning to fly aircraft not previously flown; continuation training concerns the maintenance of combat proficiency.) The bulk of the potential payoff of flight simulators lies in these latter types of training and not primarily in undergraduate training, and future R&D should concentrate on cost-effectiveness of simulators in these areas.

Consistent methods of data collection and cost-estimating should make it possible to compare the cost-effectiveness of alternative training programs, including explicit evaluations of different configurations of flight simulators, other training devices (e.g., part-task trainers) and alternative instructional strategies. Although the use of flight simulators appears to be a way of reducing training costs, the more fundamental problem is to identify where and how their use is most cost-effective (i.e., at what levels of training and for what types of aircraft, combat missions, and flight tasks and with what types of simulators and instructional strategies). Resolution of these problems requires comprehensive and compatible data and cost-estimating methods that do not now exist across the range of training programs.

The services are also using different strategies to procure flight simulators. The Air Force plans call for a large-scale procurement, while the Army is following a step-wise approach; the Navy's plan may be described as intermediate between these extremes. Judging which type of program is most appropriate was beyond the scope of this paper. Yet, it is clear that each type of program has some advantages and some risks. If flight simulators prove to be cost-effective, the Army would lose savings gained by the Air Force approach. The reverse would be true to whatever extent simulators may b found to be not cost-effective.

If the increased use of flight simulators leads to a reduction in flying hours, which appears to be likely, a fundamental question will have to be answered: namely, what is the minimum amount of continuation flying required to maintain the combat readiness of the operational flying forces. The question is hardly a trivial one. It includes consideration, not only of maintaining flying skills, but of exercising the systems which support military combat flying such as maintenance and repair, logistics, and command and control. Although there is concern about the effect that an increase in simulator time and a decrease in flying hours could have on operational readiness, no evidence was found of systematic efforts to establish the possible impact of such changes in objective terms.

C. RECOMMENDATIONS

1. *Increased emphasis should be given to cost-effectiveness analyses of all aspects of flight training.* This includes cost-effectiveness evaluations not only of flight simulators per se but of other key factors in flight training programs, such as the use of part-task and cockpit procedures trainers, the major components of flight simulators (e.g., external visual displays, platform motion and other motion cue systems), instructional procedures, and objective performance measures. All of these issues must be addressed specifically in cost-effectiveness analyses of undergraduate, transition and continuation training programs.

2. *The DoD and the military departments should develop mutually consistent data-collection systems and cost-estimating methods to improve their capabilities for analyzing the cost and effectiveness of flight training programs.* The preliminary cost model that is outlined in this report provides a starting point for both the development of analytical methods and the identification of data that should be collected. Particular attention should be given to identifying the consequences, both in cost and effectiveness, of different inputs to training programs (e.g., aircraft, flight simulators, other training devices, and instructional strategies) for all types of flight training.

3. *A DoD-wide program should be developed for RDT&E on visual systems in flight simulators.* Emphasis should be given to the development of specifications for the visual and perceptual characteristics of such displays to complement the emphasis now being given to the development of improved means of visual simulation. Cost-effectiveness analyses are needed to evaluate trade-offs between various visual specifications and engineering specifications for the major components of the new visual display systems (e.g., data storage, processing, and display.) The real question is the contribution which any improvement in any of these components might make to the cost-effectiveness of training in flight simulators; this question is both obvious and overlooked.

4. *Studies should be performed to identify the factors which account for the wide range in amounts of flight time reported as saved due to the use of simulators.* Such studies should be extended to include transition and continuation training that, together, account for 80 percent of variable flying costs in peacetime.

5. *Studies of the effectiveness of flight simulators should be designed so that their results may be evaluated on a common basis.* In practical terms, this means that standard measures of transfer of training, such as the Transfer Effectiveness Ratio, should be used in all studies supported by the DoD. Further, these studies should uniformly investigate the manner in which transfer of training varies as simulation is increasingly substituted for flying (incremental transfer effectiveness) to establish the limits to the economic use of simulators. In addition to studies of flight savings, there is a need for studies using other objective measures of the effectiveness of flight simulators, such as their impact on the quality of pilot performance, and on errors and near-accidents in flight. Systematic studies of pilot acceptance and morale should also be included.

6. *Establish the minimum number of flying hours needed to maintain the combat readiness of the operational flying forces.* The increased use of flight simulators will probably lead to a reduction of flying hours needed to maintain flight proficiency, but it will also be important to establish, in objective terms, the amount of flying needed to maintain readiness of support activities such as maintenance, logistics, and command and control.

I. CURRENT USE OF FLIGHT SIMULATORS

A. THE USE OF FLIGHT SIMULATORS TO REDUCE FLYING HOURS

Various types of flight simulators have been available for training since soon after the airplane was invented, but their actual use by the Military Services was always limited. The reasons are quite obvious: the simulators did not simulate airplanes very well and pilots preferred to practice flying in airplanes rather than in devices anchored to the ground. The situation has changed significantly over the last five years for three major reasons: (1) improved simulators are now more acceptable to pilots, (2) there has been pressure to reduce "unnecessary" military flying due to budget constraints, and (3) there is a need to conserve gasoline due, in part, to the oil embargo of 1973.

Combat flying occurs during war. In peacetime, military flying occurs for the following purposes:

Undergraduate training	- Initial flight training
Transition training	- Training to qualify for flight duty on a different type of aircraft, after initial flight training; also called type training or conversion training; includes requalification for a pilot who loses "currency" by not having flown that aircraft for some time.
Continuation training	- Training to maintain combat proficiency of pilots and flight crews assigned to organizations with a primary mission of combat in the event of conflict; also called operational training.

Support Flying - Includes Military Airlift Command, industrial fund flying, weapons development and test, airborne alert, and command support. This may also be called mission flying (or peacetime operational flying) of support forces.

In its most recent report on flight simulation to the Senate Armed Services Committee, the DoD acknowledges that "the planning goal (to reduce total flying hours by 25 percent by FY 1981) was not based on formal Service or Department of Defense studies regarding the potential for reducing flying hours through the use of simulation." (DoD Report on Flight Simulation, 1977, p. 21).[(1)] Flying for undergraduate pilot training, conversion training, and proficiency flying was to be reduced by 50 percent and for operational training by 20 percent (current terms are transition in place of conversion training, and continuation in place of operational training; the term proficiency flying is still used by the Army but no longer by the Navy and Air Force. The term applies to flying to maintain the flight skills of rated pilots while on assignment to non-flying duties, i.e., "desk-type" jobs.) Additional funds for flight simulation were added to the budget ($59M in FY 1974 and $105M in FY 1975). (Clements, 1974) Formal guidance was given to the services in 1975 (Planning and Programming Guidance for FY 1977, Secretary of Defense, February 1975).

Military flying cost about $2.7B for 6.4M hours of flight in FY 1975 and an expense of this size tends to be noticed during the budget reviews of the DoD and the Congress. A Government Accounting Office (GAO) report (1973) noted that the

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(1) Several dates may be found for the time at which the planned reduction will be achieved: Clements' letter of Feb. 20, 1974 says "in the next five years"; a staff note attached to the letter says "by 1980"; the DoD Report on Flight Simulators, February 1976 contains no date; the report for February 1977 says that "the end of FY 1981 was an initial planning goal."

civilian airlines conduct over 75 percent (now over 90 percent) of their flight training in simulators. (The airlines conduct transition, upgrading, and recurrent training. Transition training applies to qualification in new aircraft and upgrading for a difer-ent crew position in the same aircraft. Recurrent training applies to periodic recertification to insure proficiency, particularly on abnormal and emergency procedures. The airlines do not conduct undergraduate or continuation training which account for about 75 percent of all military variable flying costs). The GAO recommended that the services use simulators as much as possible to reach and maintain required proficiency levels and that they support the development of improved simulators to replace maximum amounts of training time now spent in aircraft. The Office of Management and Budget (1973) said that, based on the experience of commercial airlines and the manned space program, simulators could be substituted for flight with substantial economic benefits. In 1976, the Senate Armed Services Committee expressed concern that the use of simulators as a substitute for flight might degrade the quality of the flying forces (Senate Armed Services Committee Authorization Report for Fiscal 1976). At the same time, the Conference Committee on Appropriations wanted the DoD to increase the use of flight simulators and to integrate them into the training programs. At the request of the Senate Armed Services Committee, the DoD provided reports on its flight simulation procure-ment program for FY 1976 and FY 1977 and on its R&D program for FY 1977 (Allen, 1976).

The use of flight simulators, some still to be procured, is now expected to reduce total flying hours by 17 percent in FY 1981. Not all aircraft are supported by simulators. When flying hours for all aircraft are included, it is estimated that flying hour avoidance will be about 11 percent in FY 1978

and about 14 percent by FY 1981. It appears that studies which examine the various consequences of such reductions in flying hours, both on training programs and on operational readiness, remain to be accomplished.

B. PROCUREMENT OF FLIGHT SIMULATORS

DoD now spends about $300 million per year to procure flight simulators; the total for FY 1975-FY 1979 is about $1.5B (Table 1). This DoD report provides amortization data for 24 types of simulators (97 units) authorized or requested by the services during FY 1976-1978; the sample includes mission simulators, procedure trainers, and instrument flight simulators. Median amortization periods, to the nearest half year, are shown in Table 2 for two discount rates (6 percent and no discount). Based on the DoD estimates, the median amortization period for these flight simulators is less than 5 years at a 6 percent discount rate and less than 4 years with no discount. Department of Defense Instruction (DODI) 7041.3 *Economic Analysis and Program Evaluation for Resource Management* specifies that cost-effectiveness analyses use a discount rate of 10 percent which, if followed, would lengthen the amortization period beyond that shown in the report to Congress. If military flying costs ($2.7B in FY 1975) are actually reduced by 25 percent ($675M), the planned procurement cost of simulators ($1.5B for FY 1975-FY 1979) would be amortized in 2.2 years. This estimate makes no allowance for the costs of utilizing flight simulators, discount rates, and other factors that should be included in a full life cycle cost analysis.

There no longer appears to be a question about whether or not simulators should be procured. Rather, the current issue is to determine for what purposes and to what extent they can best be used and what performance characteristics they need to meet these

TABLE 1. SYNTHETIC FLIGHT TRAINING DEVICE PROCUREMENT FUNDING, FY 1975-1979 (Dollars in Millions)

Aircraft System/ Simulator	Approved				Requested	
	FY 1975	FY 1976	FY 197Q	FY 1977	FY 1978	FY 1979
Army						
UH-1	11.0	17.0	-	14.5	8.2	21.6
AH-1	-	-	-	-	-	32.7
CH-47	-	-	-	-	-	16.4
UTTAS	-	-	-	-	-	14.4
	11.0	17.0	-	14.5	8.2	85.1
Navy/Marine Corps						
A/TA-4	3.2	2.0	0.3	1.4	0.6	1.0
A-6	14.3	2.8	3.8	6.6	9.1	9.4
A-7	4.8	2.2	-	2.4	3.1	1.1
CH-46	5.0	1.1	0.1	1.0	13.4	2.0
CH-53	-	0.2	0.1	4.9	0.8	0.7
E-2	8.2	1.0	-	2.0	22.5	4.5
EA-6B	15.1	1.6	0.1	5.4	4.5	5.8
EC/KC-130	1.6	2.2	1.9	1.5	1.3	1.9
F-4	9.1	2.4	1.3	0.5	0.8	1.4
F-14	23.6	5.5	-	15.7	16.7	11.8
F-18	-	-	-	-	-	23.1
P-3	8.2	1.7	6.4	25.8	20.9	19.9
S-3	21.2	15.9	-	1.9	12.3	8.2
T-2	3.2	2.3	-	1.2	0.9	1.3
T-34	-	0.8	0.6	-	11.3	0.8
ACM*	12.0	-	0.1	1.0	3.8	4.3
Other	3.9	4.0	5.0	5.7	8.5	1.7
	133.5	45.7	19.7	77.0	130.5	98.9
Air Force						
A-10	-	13.2	-	22.1	28.8	10.0
B-1	-	-	-	-	25.0	47.0
B-52	1.0	27.5	-	31.1	-	-
C-5	3.0	0.6	-	11.2	-	-
C-141	3.5	2.5	-	9.3	-	-
C-130	15.0	7.7	-	29.5	50.1	50.6
F-15	6.0	17.2	-	19.-	29.9	21.9
F-16	-	-	-	-	38.0	26.9
F-111	-	-	-	9.9	-	-
KC-135	0.7	17.1	-	24.3	-	-
T-37/38 (UPT-IFS)	34.0	39.5	10.3	52.9	12.4	-
SEWT**	-	4.0	-	-	-	-
	63.2	129.3	10.3	209.3	184.2	156.4
TOTAL	207.7	192.0	30.0	300.8	322.9	340.4

* Air Combat Maneuvering Simulator
** Simulator for Electronic Warfare Training
Source: DoD Report on Flight Simulation, 1976, 1977

TABLE 2. MEDIAN AMORTIZATION PERIODS FOR 97 UNITS OF 24 SIMULATORS AUTHORIZED OR REQUESTED, FY 1976 - 1978

	No. of Simulator Types	Median Amortization Period: 6 percent Discount	Median Amortization Period: No Discount
Army	3	4.5 years	3.8 years
Navy/Marine Corps	12	4.5	3.5
Air Force	9	6.0	5.2
Total	24	4.8 years	3.8 years

Source: DoD Report on Flight Simulation, 1977

requirements. Subsequent chapters of this report review information already available about the cost and effectiveness of flight simulators and consider R&D that is needed to deal with issues that cannot be resolved at present.

C. UNDERGRADUATE PILOT TRAINING

The undergraduate pilot training loads of the military services for FY 1976-FY 1979 are shown in Table 3. The training load is the average number of student pilots in training during the year, including an allowance for losses due to attrition. The training load (about 3000 in FY 1978) has been declining since FY 1974 but will rise in the future as aviators from the Vietnam period leave the services and have to be replaced. Course lengths and anticipated attrition for FY 1978 are as follows:

	Course Length	Anticipated Attrition
Army	34-40 weeks	10-25 percent
Navy/Marine Corps	40-63 weeks	15-30 percent
Air Force	48.5 weeks	13.5 percent

Undergraduate pilot training cost about $150K per pilot in FY 1975, according to a Defense Audit Report (1976), and about $125K in FY 1976, according to a Defense Science Board report (1976, p.31). It is by far the most expensive type of training provided by the Armed Forces. The obligational authority for flight training in FY 1977 was $996M for 5900 student man-years of training, i.e., load. (Congressional Budget Office 1977, p.9). Yet, it is important to remember that this accounts only for undergraduate flight training at 15 flight training bases, i.e., "school house training". Most military flying, such as for transition training, combat training, and for maintenance of readiness, takes place in operational units and is not reported as a cost of training. The distribution of variable flying costs for various types of flying shows that about 10 percent is for undergraduate flight training and the remainder for other types of flying.

TABLE 3. TRAINING LOADS, UNDERGRADUATE PILOT TRAINING, FY 1976-79 AND INPUT AND OUTPUT, FY 1978

Service Component	FY 76 Load	FY 77 Load	FY 78 Input	FY 78 Output	FY 78 Load	FY 79 Load
Army						
Active	604	567	974	665	599	693
Reserve	1	-	28	24	17	17
National Guard	2	-	45	36	28	28
Navy						
Active	1,010	877	1,210	800	840	910
USMC						
Active	424	509	644	382	455	522
Air Force						
Active	1,280	1.097	1,208	1,050	1,034	1,113
Reserve	24	20	24	21	21	21
National Guard	69	72	84	71	71	71
DoD						
Active	3,318	3,050	4,036	2,897	2,928	3,238
Reserve/Grand Total	96	92	181	152	137	137
DoD Total	3,414	3,142	4,217	3,049	3,065	3,375

Source: Military Manpower Training Report, FY 1978

Percentage of Variable Flying Costs (FY 1981)

Type of flying	Air Force	Navy
Undergraduate flight training	9%	9%
Transition/type training	11	15
Continuation training	75	67
Support flying	4	9
Total	100%	100%

Sources: USAF Program, Aerospace Vehicles and Flying Hours, Vol. 1, 7 May 1976 (SECRET)

USAF Cost and Planning Factors (AFR 173-10) (CONF)

Aircraft Program Data File (APDF), Navy, Jan. 1977 (SECRET)

See this report, Vol. II, Tables 1 and 2.

D. ADVANTAGES OF FLIGHT SIMULATORS

Flight simulators have the following advantages for training:

1. They permit full attention to the tasks on which training is to occur without waste of time on tasks directly relevant to that purpose (e.g., no need to practice take-off and to fly around the airport when training for landing or to cruise to the gunnery range when training for air-to-air ground gunnery.)
2. They permit observation of performance by an instructor pilot that is not possible in a single-seated aircraft.
3. They provide objective measurement of performance not ordinarily available in most aircraft.
4. They provide immediate feedback on performance, repeating trials, and freezing the status of the airplane, as desired by the plan of instruction.
5. They permit scheduling of training regardless of weather, air traffic, availability of aircraft, targets, ammunition, fuel, and airspace.

6. They provide experience on dangerous maneuvers and on flight conditions encountered only rarely without risk to safety.
7. They can accommodate advanced instructional methods, e.g., simplify a task or make it more difficult, they are self-pacing, permit computer-aided instruction, enable desirable sequencing of flight tasks, etc.
8. They permit rigid control of flight conditions and other factors which may be of interest for training or experimental purposes.
9. They permit gradual exploration of all portions of the flight envelope.
10. They cost less to operate than aircraft (save fuel and ammunition, extend the service life of aircraft, and avoid accidents).

In short, simulators can provide certain types of training more effectively and less expensively than aircraft. The major disadvantage of a simulator is that it is not an airplane and it cannot be substituted for one. Thus, it cannot provide the stress and experience in coping with unexpected events that can occur in actual flight. No serious discussion was found concerning the disadvantages of flight simulators.

Pilots are not known for their enthusiasm about the use of flight simulators. In 1969, an Air Force Committee reported that "There are numerous simulators in the Air Force inventory that are not fully utilized for various reasons. This may stem, in part, from the lack of emphasis placed on using simulation in lieu of flying" (taken from Alsobrook, 1975, p.3). Alsobrook found, in a survey of about 450 pilots and navigators, that at least one-third either moderately or strongly disliked flying the simulator; the remainder were either neutral or favorable. Lack of realism and inability to stimulate the feelings involved in flying are given as the major objections to the simulators. Youngling et al (1977) report that pilots would be willing to spend about 40 percent of their flying time in simulators for training

on general procedures, instrument flying and communications coordination, but 20 percent or less on all other functions (e.g., takeoff, landing, air-to-air combat, air-to-ground attack). Two-thirds of this sample of about 375 were pilots with at least five air combat kills.

No matter how wonderful the simulator may be, a pilot needs to learn to fly an airplane and not a simulator. Thus, the question about how best to train a pilot really concerns the most effective distribution of tasks in the training curriculum between the simulator and the aircraft for producing a qualified pilot at the least overall total cost. The policy decision that flying hours will be reduced by 25 percent and hence that some of the training accomplished in aircraft should be accomplished in simulators is not as radical as it may appear. A certain amount of training has always been conducted in flight simulators. For years, test pilots have become acquainted with the flight characteristics of new aircraft in simulators before taking the aircraft off the ground for the first time. A well-known example of total reliance on flight simulators for training is the case of the astronauts who had no previous experience with orbital flight, rendezvous, or landing on the moon, except that gained (at great expense) from the 15 different simulators used in the Apollo program. Each crewman trained for almost 1000 hours (the equivalent of twenty-five 40-hour weeks) in these simulators, most of the training (84 percent) was in the command module and lunar module full-mission simulators. (Wooding et al, 1973). The training program for the crew of the Space Shuttle involves the use of 11 simulators, two aircraft modified to simulate some flight characteristics of the Shuttle, and a KC-135 to provide heavy aircraft training. The FAA has permitted American Airlines to test a transition training program in which a pilot flies a B-747 for the first time on a regularly scheduled flight after training only in the B-747 simulator. A supervisory pilot monitors

the pilot's performance until he is judged to be fully qualified; the pilot cannot be considered a novice, since he is already fully qualified in the B-707.

The GAO (1973) has suggested that the use of flight simulators by the airlines should serve as a model for the military. However, the circumstances of the airlines and of the military services with respect to training pilots are not directly comparable, except for the transport operations of the Military Airlift Command. Beyond that, military training is for combat operations involving the use of weapons and countermeasures in highly maneuverable craft, hardly a task for the airlines. The military services conduct undergraduate pilot training, the airlines do not. Both conduct transition training (i.e., upgrade pilots to fly aircraft not previously flown), refresher training (new procedures and regulations) and recertification (periodic performance evaluation and quality control). Airline pilots fly more frequently than military pilots, i.e., about 50 hours per month (with a maximum of 80) in comparison to 5 to 10 hours per month for the military. Since a commercial flight brings in money to the airlines, their pilots are encouraged to fly up to the limit supported by the market. A military flight appears to be an expense to the taxpayer and there are pressures to reduce military flying. It is helpful to remember that the ultimate purpose of military flying is to assure success in battle.

Commercial airlines appear to use their simulators more extensively than the military services, perhaps 18 to 20 hours a day, 7 days a week in comparison to 8 to 16 hours a day, 5 to 6 days a week for the military.

In addition to their many other advantages for training pilots, flight simulators can be operated at costs that appear to vary from 5 to 20 percent of the equivalent airplane (this topic is considered more fully later in the report). This does not mean that flight simulators are inexpensive devices either to procure or to operate.

Helicopter simulators cost from $4 to $10M each (some provide four cockpits); the F-4, C-5, F-15 simulators are in the range of $3 to $7M each, excluding the cost of development; the Advanced Simulator for Undergraduate Pilot Training (ASUPT), an experimental device, cost about $24M to procure.

An estimate of how much it costs to operate a simulator depends heavily on the rate provided for amortization (if relevant), on the assumed student load, on the hours of utilization per week, and on the manning policies associated with its deployment. An estimate of how much it costs per hour to operate the comparable airplane depends not only on its amortization schedule (if relevant), but on what items are included in flying costs (e.g., fuel, maintenance, spare parts, base support, etc.). The cost-effectiveness of aircraft and simulators depends not only on their operating cost, but also, clearly, upon how they are used, i.e., their effectiveness as training devices. We should anticipate that even though simulators generally cost less to operate than aircraft, they may not always be so effective as to provide a cost-effective alternative in all applications.

There are two major issues concerning the large number of flight simulators to be procured by the Department of Defense: (1) for what types of aircraft and for what types of training are flight simulators more cost-effective than aircraft, and (2) what performance characteristics are needed to make flight simulators cost-effective for various types of training. These are not trivial issues. The major application of flight simulators by the military services has been for undergraduate pilot training, followed by transition training. Yet, over 50 percent of all military flying hours and 65 to 75 percent of all variable flying costs (varying by service) are for continuation training, i.e., to maintain the skills necessary to perform combat missions. Thus, the appropriate question is to determine the extent to which flight simulators can be used to supplement and/or substitute for all types of military flight training, and not only undergraduate pilot training.

The performance characteristics of flight simulators affect not only their cost, but also their potential effectiveness as training devices for the many different skills required to fly advanced aircraft. For example, platform motion and visual display systems are high cost items in the flight simulators soon to be procured. The issue of what they contribute to training is discussed later in the report.

E. RDT&E ON FLIGHT SIMULATION

About $27M (35 percent) of all DoD RDT&E on military training ($79M) in FY 1977 was allocated to flight simulation; about $1.7M was allocated to RDT&E on the cost-effectiveness of training; almost none of the latter was concerned with flight training (Orlansky, 1977). A few cost-effectiveness analyses of flight simulation have been conducted with non-RDT&E funds by operational and training commands (see Chapter IV). Current policy guidance of the DoD calls for determining the cost-effectiveness of flight simulators for training purposes (SecDef 1977, p. III-88).

About half the RDT&E on flight simulation is supported by the Air Force, followed by the Army and Navy. These funds were expended for the following categories of RDT&E activities:

6.1	Research	$ 0.2M	1 percent
6.2	Exploratory Development	2.0	7
6.3	Advanced Development	8.7	32
6.4	Engineering Development	12.9	47
6.5	Management and Support	-	-
IR&D	Independent R&D	3.6	13
		$27.4M	100 percent

About half of the funds are spent for the engineering development (category 6.4) of prototype components and subsystems for flight simulators; a lesser amount is spent for Exploratory and Advanced Development (6.2, 6.3), a pattern generally observable in most areas of technology. The small amount of funds for Research (6.1)

on flight simulation warrants notice but defies explanation. A more detailed review of the RDT&E activities appears in Chapter V.

II. OPERATING COSTS OF SIMULATORS AND AIRCRAFT

The case for flight simulators always includes the argument that they cost less to operate than aircraft. This statement appears to be correct, even though data to support it are incomplete and have not been collected systematically. More reliable information could become available if improved procedures are instituted to collect cost data concerned specifically with training and the use of flight simulators. The current situation is described by the following statements:

> "The data base for simulator cost estimation is virtually nonexistent....A study to develop sound models for cost benefit analysis of simulator capital investment decisions is very much in order." (Air Force Master Plan, 1975, p.124)

The Defense Audit Service (1976) notes that the military services have not analyzed their allocation of resources for undergraduate flight training:

(1) "The Army had acquired 24 flight simulator cockpits without preparing the economic analysis and cost-effectiveness studies required by DoD Instruction 7041.3" (p.23).

(2) "The Navy acquired 5 flight simulator cockpits without preparing the required economic analyses and cost effectiveness studies." (p.24)

(3) "As of October 1975, the Air Force proposed to acquire 24 Instrument Flight Simulator Systems consisting of 96 simulator cockpits at a cost of $192 million for its

> Undergraduate Pilot Training Program without preparing up-to-date economic analyses and cost effectiveness studies." (p.24)[1]

It is not a trivial matter to establish operating or life-cycle costs to be used in cost-effectiveness studies because the result depends significantly on the treatment accorded to such factors as base support, depreciation of aircraft, aircraft attrition, amortization of investment in flight simulators, utilization rates, maintenance, and repair requirements.

Data from a variety of sources were collected to establish an order of magnitude for the costs per hour of operating selected simulators and their counterpart aircraft (Table 4). Most of the data come from Air Force sources, but Army, Navy, and commercial sources are also used. The apparently simple comparison of operating costs presented in this report rests on assumptions which are best made explicit. The cost of operating an aircraft is taken as the variable flying cost per hour, a value which can be compared to the cost of operating a simulator for an hour. Only costs attributable to operations were included; amortization costs and crew salaries were excluded. Only costs based on how aircraft and simulators were actually utilized during the period of observation (FY 1975 and FY 1976) were used; no estimates were made about what the costs might be under some assumed standard condition, such as flying aircraft for 700 hours per year or operating simulators for 80 hours per week. No assurance can be offered that data taken from different sources were compiled according to the same rules. No assumption was made about how much training is provided by one hour of training in a simulator or in an aircraft for any member of the air crew. Thus, if these many qualifications can be accepted, the data apply only to the cost of operating a simulator or an

(1) The original economic analysis in "Mission Analysis on Future Undergraduate Pilot Training System, 1975-1990", AFSC-TR-72-001, January 1972 appears not to have been updated in connection with this proposed procurement.

TABLE 4. SUMMARY OF VARIABLE OPERATING COSTS OF SOME SIMULATORS AND AIRCRAFT, FY 1975 and FY 1976 (Data in Appendix A)

	N	Range	Median
Operating cost per hour			
Simulator	49	\$ 9 - \$ 275	\$ 96
Aircraft	42	\$63 - \$3610	\$1066
Cost ratio: Simulator/aircraft operating cost per hour	33	0.02 - 0.40	0.116

airplane. The results of interest are summarized in Table 4; details appear in Appendix A. The median variable operating cost of 49 simulators is $96 per hour; and of 42 aircraft is $1066 per hour. The median cost ratio of simulator/aircraft operating cost per hour for 33 cases where both costs were available is 0.116. Excluding the three largest ratios, all remaining ratios (91 percent) are 0.24 or less. On the basis of operating cost alone, it appears that it costs very much less to operate a simulator than an airplane.

These values, of course, say nothing about the capability of these various simulators for training. The simulators in this table vary markedly in their complexity and operating cost. Only a few of them may be called modern, fully capable simulators, e.g., the Navy P-3C (2F87F), the Coast Guard HH-52A and HH-3F (VCTS), and the B-747 and DC-10 simulators. Even if it takes more time to train on a particular take in the simulator than in the aircraft, it is economical to do so up to the point determined by the simulator/aircraft operating cost ratio. It is a matter of considerable interest that few data are now available for comparing required training times for various tasks in the simulator and/or the aircraft and, as well, for comparing those results with the appropriate operating cost ratios.

As noted above, the operating costs of the flight simulators shown in Figure 1 are based on actual rather than on theoretical utilization rates. For a limited sample of 38 simulators, utilization varied from 14-99 hours per week with a median of 37 hours; the median operating cost was $88 per hour. Assuming a standard utilization rate of 80 hours a week for all simulators, the median operating cost of the same simulators would be $36 per hour; however, this estimate does not take account of such factors as increased manning and maintenance which would occur with increased utilization. In the airline industry, utilization rates of flight simulation are estimated to be 100-125 hours per week.

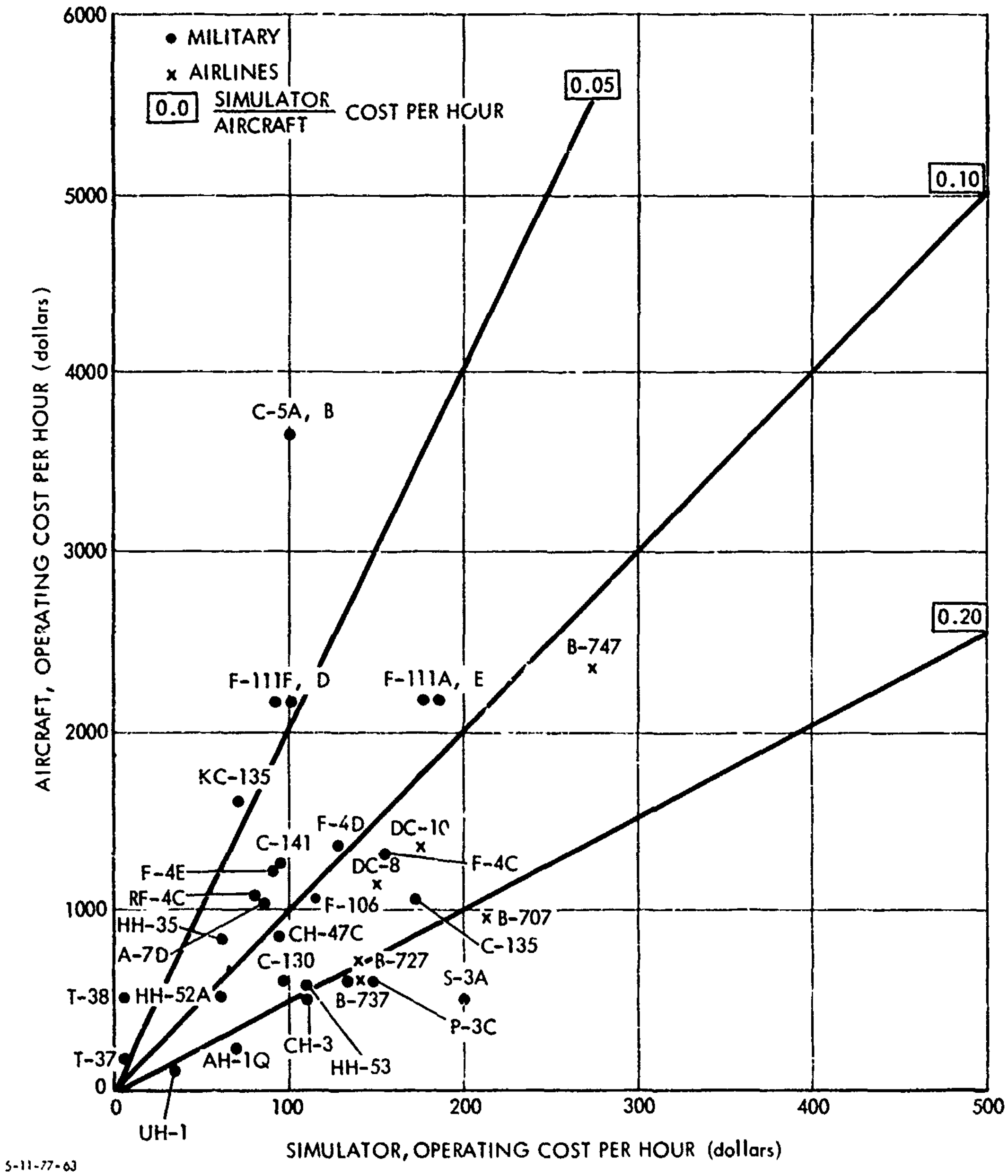

FIGURE 1. Variable operating costs per hour for some simulators and aircraft, FY 1975 and FY 1976. (Data from Appendix A)

A comparison of operating costs is based on the premise that the services have (or would have) purchased aircraft primarily to accomplish assigned military purposes and that the use of these aircraft for other purposes, such as training, leads to the accrual of no additional costs, except those due specifically to training use. Thus, all costs (investment, O&M) are excluded, except for the variable operating costs attributable to training. Some factors which generally favor the use of simulators are excluded from consideration. These would include extending the useful life of aircraft by reducing the required number of flying hours per year (or reducing the required inventory of aircraft by an equivalent amount), reduced attrition of aircraft and of personnel due to fewer accidents with reduced flight time (unless the actual trend is in the opposite direction), need for fewer airbases and less air space for training (if the reduced number of flying hours and/or aircraft are in large enough units to produce such effects), and the like.

Advanced simulators will have greater capabilities and will probably be more expensive to operate than those in current use. (ASPT, an advanced flight simulator with special features needed for experiments on training, costs $950 an hour to operate; this is not, of course, routine training.) Even if the cost ratios for advanced simulators are less favorable than those shown here, it will probably still cost less to operate a simulator than an airplane. However, operating costs (or any other indicators of cost) are not by themselves very significant for evaluating effectiveness of training without performance measures of the amount and type of training that can be accomplished either in the simulator or in the aircraft that are being compared. It is conceivable that a simulator could even cost more to operate per hour than an aircraft and still be cost-effective for certain types of training. That depends on just how the simulator and the aircraft can be and actually are used for training purposes. For example, it may be possible to perform 30 landings an hour in a simulator but

only six in an aircraft; it may be possible to conduct 10 to 15 air-to-air engagements with "missiles" in a simulator per hour but only five without missiles in the air. However, effectiveness data are in poor supply and further discussion of the cost-and-effectiveness of flight simulators and aircraft is not warranted here. On cost grounds alone, simulators appear to be a bargain. The need for effectiveness data should be apparent.

III. EFFECTIVENESS OF FLIGHT SIMULATORS

A. BACKGROUND

Research conducted over the last 35 years shows, beyond reasonable doubt, that flight simulators can be used to train pilots and other crew members on a wide variety of flight related skills. This research has been reviewed many times and the interested reader is referred to some of the more thorough, recent efforts:

Smode, Hall, and Meyer (1967)
Valverde (1968)
Carter (1971)
Micheli (1972)
Human Factors (1973)
Johnson, Knight, and Sugarman (1975)
Chalk and Wasserman (1976)
Caro (1976, 1977a,b)
Diehl and Ryan (1977)

Useful information may also be found in the reports of many conferences on flight simulation for training, such as the nine annual NTEC/Industry Conference Proceedings and the AIAA Visual and Motion Simulation Conference (1976).

About 33 studies which show that flight simulators are effective for training purposes are summarized in Appendix B. These studies were conducted over a wide period of time, 1939 to 1977; the list is not necessarily complete. The summary draws primarily on information contained in Carter (1971), Micheli (1972), Diehl and Ryan (1977), and on other sources identified in the text.

The major conclusions that may be drawn from these studies are:

1. Training in simulators reduces the time otherwise needed to acquire the same skills in aircraft. Many well-controlled studies show that simulators can be used to train pilots on flight procedures, takeoff, approach and landing, flight maneuvers, and instrument flight.
2. Many of the studies used college students to show that there is positive transfer of training from simple simulators to simple aircraft. About 20 studies since 1970 show similar results for military students and highly experienced pilots using modern flight simulators for current jet, turboprop, and helicopter aircraft.
3. Flight simulators appear to be most effective for training on tasks that involve following precise procedures such as in instrument flight and approach and landing.
4. The amount of transfer of training from simulator to aircraft varies widely among these studies. Few of the studies report the amount of transfer in a consistent way. Few studies have examined systematically the factors that influence the transfer of training. However, comparable measures of transfer can often be calculated from available data and such results are reported below.
5. The way in which the simulator is used can significantly influence its effectiveness as a training device. Among the factors known to influence training are the training syllabus itself, the type of feedback given the pilot, the selection and training of instructor pilots, and whether the same instructor pilot provides training both in the simulator and the aircraft.

Although these conclusions are regarded as well-founded, they provide only limited guidance for the current acquisition and use of flight simulators.

B. MEASURES OF TRANSFER OF TRAINING

The term "effectiveness" must be taken in its strict literal sense, i.e., that simulators can be used to teach flying skills that transfer to the aircraft. The question of whether it is economical to use simulators, i.e., cost-effective, is not considered in most of these studies, a matter which is discussed in the next chapter. For example, "Handbook for Training Systems Evaluation" by Jeantheau (1970) does not consider costs of training.

Studies of effectiveness completed before about 1970 were performed on simulators with performance characteristics that are obsolete by present standards, particularly with regard to vision, platform motion, and instructional features. These studies, as well as many more recent ones, lack a common measure of the effectiveness of training, that is, of the amount of training carried over from a particular simulator or method of training to the aircraft. Such a common measure, or measures, is needed to compare the effects of many factors that may influence training, such as the design of the simulator (e.g., its motion and visual systems), the way in which it is used (e.g., instructional features, scoring systems), and even who uses it for training (e.g., undergraduate and/or experienced pilots).

This problem was noted most recently by Roscoe (1971, 1972) who proposed that certain measures be used systematically to estimate the effectiveness of various factors which might influence flight training. Various ways of measuring transfer of training have been reviewed previously by Gagne, Foster, and Crosley (1948) and Murdock (1957). We found several closely related measures to which some investigators gave different names. Without adjudicating possible claims for originality, we attribute Percent Transfer, Transfer Effectiveness Ratio (TER), and Incremental Transfer Effectiveness Function (ITEF) to Roscoe (1971, 1972); Replacement Ratio to Carter (1971); and Flight Substitution Ratio (FSR) to Diehl and Ryan (1977). These are defined below, and some redundant terms are also noted.

Percent transfer indicates the amount of time saved in inflight training due to the simulator and/or other training innovations, e.g., revised syllabus. Carter calls this Replacement Percent. Diehl and Ryan call this Percent Flight Syllabus Reduction. Carter uses Percent Transfer to indicate improvement in performance at the end of a fixed amount of time or trials. Percent transfer is sometimes called Percent Savings.

$$\text{Percent Transfer} = \frac{Y_c - Y_x}{Y_c} \times 100$$

Y_c = time, trials, or errors required by a control group to reach a performance criterion.

Y_x = the corresponding measure for an experimental group which has received prior practice on another task.

Transfer Effectiveness Ratio (TER) compares the flight hours saved to the time spent in the simulator. Roscoe also uses the term Cumulative Transfer Effectiveness Ratio, as equivalent to the TER. Carter uses CTER to indicate Cumulative Transfer Efficiency Ratio. The TER is the reciprocal of Carter's Replacement Ratio and also (approximately) of Diehl and Ryan's similar, but not identical, Flight Substitution Ratio. The "Air Force Master Plan--Simulators for Air Crew Training" (1975) uses Training Transfer Ratio (number of hours in simulator/number of hours in aircraft for equivalent training).

Transfer Effectiveness Ratio (TER) = $\frac{Y_o - Y_x}{X}$

Y_o = time, trials, or errors required by a control group to reach a performance criterion, (same as Y_c above, where X = zero, for the control group)

Y_x = corresponding measure for experimental group receiving x-training units on a prior task (same as Y_x above).

X = time, trials, or errors by an experimental group during prior practice on another task to achieve the savings represented by $Y_o - Y_x$.

Incremental Transfer Effectiveness Ratio (ITER) indicates the efficiency of additional amounts of training. Carter calls ITER Incremental Transfer Efficiency Ratio.

Incremental Transfer Effectiveness Function (ITEF)

$$= \frac{Y_{x - \Delta x} - Y_x}{\Delta x}$$

$Y_x - \Delta x$ = time, trials, or errors required to reach a performance criterion by an experimental group having received Y-Δx training units on a prior or interpolated task.

Y_x = corresponding measure for an experimental group having received X training units on a prior task (same as Y_x above)

Δx = incremental unit of time, trials, or errors during prior practice on another task.

Replacement Ratio is an index of training efficiency used by Carter before he learned about the TER, of which it is the reciprocal.

$$\text{Replacement ratio} = \frac{X_E}{Y_c - Y_E}$$

X_E = time required by the experimental group in the training device or method to achieve the time ranges represented on $Y_c - Y_E$

Y_c = time required in the criterion device by the control group

Y_E = time required in the criterion device by the experimental group.

Flight Substitution Ratio (FSR) is the rate at which flight time is being replaced by simulator time and reflects changes in both.

$$\text{Flight Substitution Ratio (FSR)} = \frac{X_E - X_C}{Y_C - Y_E}$$

X_E = time required in simulator by experimental group

X_C = time required in simulator by control group

Y_C = time required in aircraft by control group

Y_E = time required in aircraft by experimental group

C. FINDINGS ON THE EFFECTIVENESS OF FLIGHT SIMULATORS

Standard measures of transfer of training tend to appear in review articles and infrequently in research reports, with some recent exceptions. However, they can be calculated easily provided of course, the required data are reported; namely, the hours spent in training on a particular task to some specified level of

proficiency in a simulator and in an aircraft. The effectiveness of flight simulators as training devices was calculated for three measures of transfer of training, based on data appearing in reports issued from 1967 to 1977. The primary source of much of this information was Diehl and Ryan (1977), whose calculations were verified; original sources were also used. The three measures were Percent Transfer, Transfer Effectiveness Ratio (TER), and Flight Substitution Ratio (FSR). For the first two measures, larger values indicate greater effectiveness for the simulator; for the FSR (which is a reciprocal of the TER except that it explicitly considers savings in simulator time), smaller numbers indicate greater transfer, i.e., that use of the simulator increases (rather than decreases) the amount of time needed to train for a task in the aircraft. Some anomalies due to the way in which the index of transfer is calculated are noted below. Diehl and Ryan (1977) appear to be the first to use the FSR; the other indices have been used in some previous studies.

The results, shown in Table 5, are clear: with a few exceptions to be noted below, simulators are effective for training purposes, i.e., they show positive transfer effects to the aircraft. The use of flight simulators for training saves flight time. However, there are wide variations in the effectiveness of different flight simulators and of the same simulator when used for different types of training. The information shown in Table 5 may be summarized as follows:

TABLE 5. TRANSFER OF TRAINING MEASURES, CALCULATED FROM REPORTED INFORMATION

Tasks	Aircraft	Simulator	Student* Experience	Simulator Capabilities	Curriculum Features	Percent Transfer	Transfer Effectiveness Ratio	Flight Substitution Ratio	References
Contact/ Familiarization	Piper Cherokee	AN-T-18	Undergraduate	-	Special Syllabus	20	0.8	1.2	Povenmire and Roscoe (1971)
Contact/ Familiarization	Piper Cherokee	GAT-1	Undergraduate	-	Special Syllabus	24	1.0	1.0	Povenmire and Roscoe (1973)
Contact/ Familiarization	Light Plane	?	Undergraduate	-	-	16	0.4	2.3	Crook (1967)
Instruments	Light Plane	?	Graduate	-	-	48	1.1	0.9	Crook (1967)
Transition	B-747	B-747	Highly Experienced	Visual/ Motion	Special Syllabus Part-Task Trainer	64	0.2	-2.6	Melden and Houston (1975)
Transition	B-707	B-707	Highly Experienced	Visual/ Motion	Special Syllabus Part-Task Trainer	90	0.6	-0.7	" " "
Transition	B-727	B-727	Highly Experienced	Visual/ Motion	Special Syllabus Part-Task Trainer	89	0.6	-0.9	" " "
Transition	DC-10	DC-10	Highly Experienced	Visual/ Motion	Special Syllabus Part-Task Trainer	23	0.03	-8.0	" " "
Instruments	UH-1	2B24	Undergraduate	Motion	Special Syllabus	89	1.2	0.8	Caro (1973)

*Undergraduate refers to military UPT programs and general aviation student pilot training programs
Graduate refers to designated military pilots and licensed general aviation pilots
Highly Experienced refers to airline pilots
Naive refers to no previous flight experience

Sources: Diehl and Ryan (1977), Micheli (1972) and original sources.

TABLE 5 (Continued)

Tasks	Aircraft	Simulator	Student* Experience	Simulator Capabilities	Curriculum Features	Percent Transfer	Transfer Effectiveness Ratio	Flight Substitution Ratio	References
Qualifications	H-52	VCTS	Graduate	Motion	Special Syllabus Part-Task Trainer	54	1.9	0.5	Isley, Corley and Caro (1974)
Transition	H-52	VCTS	Graduate	Motion	Special Syllabus Part-Task Trainer	10	0.2	5.8	Isley, Corley and Caro (1974)
Transition	H-3	VCTS	Graduate	Motion	Special Syllabus	36	0.4	2.3	Isley, Corley and Caro (1974)
Transition	H-3	T-42	Graduate	Motion	Special Syllabus Part-Task Trainer	41	1.4	0.7	USAF (1974)
Contact/ Familiarization	T-37	T-4G	Undergraduate	Visual/ Motion	Special Syllabus	15	0.3	3.7	Woodruff, Smith and Morris (1974)
Instruments	T-37	T-4G	Undergraduate	Visual/ Motion	Special Syllabus	53	0.7	-0.8	Woodruff, Smith and Morris (1974)
Familiarization, Instrument Flight	T-37	ASUPT	Undergraduate	Visual/ Motion	Basic and Presolo	45	0.6	-	Woodruff, Smith, Fuller and Weyer (1976)
					Advanced Contact	4	0.1	-	
					Instruments	38	0.5	-	
					Formation	13	1.0	-	
					Navigation	13	0.2	-	
					Total	23	0.4	2.1	
Instruments	TA-4	2F90	Undergraduate	Motion	-	52	0.5	0.4	Ryan, Puig, Micheli and Clark (1972)
Instruments	TA-4	2F90	Undergraduate	Motion	-	46	0.6	0.4	O'Connor and Glennon (1973)
Instruments	TA-4	2F90	Undergraduate	Motion	-	01	-	42.0	O'Connor and Glennon (1973)
Familiarization, Instrument Flight	P-3	2F69	Graduate	Motion	Special Syllabus Part-Task Trainer	39	0.6	0.3	Browning, Ryan and Scott (1973)

TABLE 5 (Continued)

Tasks	Aircraft	Simulator	Student* Experience	Simulator Capabilities	Curriculum Features	Percent Transfer	Transfer Effectiveness Ratio	Flight Substitution Ratio	References
Familiarization, Instrument Flight	P-3	2F87F	Graduate	Visual/ Motion	-	43	0.3	2.3	Browning, Ryan, Scott and Smode (1977)
Familiarization, Instrument Flight	E-2	2F65	Graduate	-	-	-11	-0.4	∞	Diehl and Ryan, Ref. 22 (1977)
Familiarization, Instrument Flight	C-130	T-19	Graduate	Motion	Special Syllabus Part-Task Trainer	22	0.2	0.4	Diehl and Ryan, Ref. 23 (1977)
Familiarization, Instrument Flight	C-141	T-37A	Graduate	Visual/ Motion	Part-Task Trainer	15	0.1	15.4	Diehl and Ryan, Ref. 24 (1977)
Familiarization, Instrument Flight	T-42	GAT-2	Undergraduate	Motion	Special Syllabus	42	1.0	0.2	Caro, Isley and Jolley (1973)
Procedures; Takeoff; Hover, Landing	Helicopter	Whirlymite	-	-	-	9	0.17	-	Caro (1968)
Flight Procedures Maneuvers	B-707	B-707	Highly Experienced	-	-	49	0.19	-	TWA Training Dept. (1969)
Flight Procedures and Maneuvers	DC-8	DC-8	Highly Experienced	-	-	13	0.41	-	Meyer, Flexman (1967) Van Gundy, Killiam and Lanahan
Private Pilot Certification	Piper Cherokee Arrow	GAT-2	Naive	No motion Motion Random Motion	Highly Standardized	36 34 23	0.30 0.31 0.25	3.2 3.3 4.0	Jacobs and Roscoe (1975)

TABLE 5 (Continued)

Tasks	Aircraft	Simulator	Student* Experience	Simulator Capabilities	Curriculum Features	Percent Transfer	Transfer Effectiveness Ratio	Flight Substitution Ratio	References
Night Carrier Landing	A7E	Night Carrier Landing Device 2F103	Pilots with no previous A7E experience (N=53)	Visual $40^\circ \times 30^\circ$ V Motion: 3 DOF	80 final approach control trials in simulator vs none for control group; latter received familiarity training in simulator; objective performance measures by radar on carrier landing.	-(1)	-	-	Brictson and Burger (1976)

(1) Radar measures show that simulator trained pilots show more precision in vertical flight control than those who did not; attrition rate lower, for newly designated pilots with simulator training (8 percent) than for those who did not get such training (44 percent). Flight time savings not measured.

Index	Range	Median
Percent Transfer (percent)	-11 to 90	31
Transfer Effectiveness Ratio	-0.4 to 1.9	0.45
Flight Substitution Ratio	-8.0 to 42	1.25

The median values of all indices show positive transfer but will not be interpreted further because of the wide differences in experimental procedures, tasks, pilot populations, and the like. Clearly, it would be important to understand the influences that account for large and small amounts of transfer.

These three indices are not, of course, independent measures, as the following correlations, based on Table 5, show:

	r	N
Percent Transfer - Transfer Effectiveness Ratio	0.49	32
Percent Transfer - Flight Substitution Ratio	-0.45	28
Transfer Effectiveness Ratio - Flight Substitution Ratio	-0.22	27

The negative correlations result from the Flight Substitution Ratio's reciprocal relation to the other measures. A crude interpretation of these correlations is that Percent Transfer provides about the same ordering of results with respect to transfer as would either the Transfer Effectiveness Ratio or the Flight Substitution Ratio. The relationship between the Transfer Effectiveness Ratio and the Flight Substitution Ratio is not as strong.

Certain types of training can produce negative results (a fact well known to golfers) and a few such instances appear in the table. Negative FSR's are shown for four commercial aircraft. The negative values arise in the computation because, due to improvements in the flight curriculum, fewer simulator hours are required now (for the experimental group) than previously (for the control group). Flight hours, of course, have also been reduced. The airlines operate a highly effective program in which both flight

time and simulator time have been reduced markedly over the last 10 years. This suggests that the FSR can give a notably misleading impression. No information is available to explain the other negative measures in the table.

It would be most interesting to be able to explain the wide variations in the effectiveness of flight training programs suggested by this table because this is clearly an important topic. For example, the capability of the simulators used in these studies varies widely with respect to vision and motion. The visual systems vary in field of view (48°W x 36°H to 240°W x 180°H) and in how the image is generated (model board versus computer-generated); some simulators have no visual system. The motion systems have 3 to 6 degrees of freedom, while some have none; the responsiveness of the drive mechanism (which would have to be determined in each case) is at least as important as the number of degrees of freedom. The way in which the simulator was used, e.g., type of syllabus, flight task, would clearly affect its potential effectiveness. An attempt to interpret variations in the effectiveness of flight simulators on the basis of the data shown in Table 5 is not warranted and could not be accomplished without considerable additional effort.

Diehl and Ryan (1977) are not so constrained, and we report their observations:

- Simulators provide more flight savings for instrument flight tasks than for contact-type tasks.
- Commercial airlines have achieved more flight savings from simulators than general aviation or the military.
- Simulators have been used more effectively for helicopter training and less so for jet and transport training.
- Simulators save more time in graduate and transition training than in undergraduate training.
- Simulators equipped with visual systems save more time than devices not so equipped but at a lower rate of substitution.

- Simulators with high fidelity motion systems save more time than devices without such systems
- Special syllabi, oriented towards the flight simulator, produce greater savings.
- Part-task trainers used with new simulators lead to greater savings and better substitution ratios.

These observations may turn out to be correct, but they are not well supported by currently available data. Simulators equipped with visual systems cannot properly be compared to those without such systems because they are not used for the same purposes. Visual systems are needed for training in such tasks as landing, air-to-ground attack, and air-to-air attack; systems without visual devices are useful for training in instrument flight, navigation, the use of radar, and have, of course, been used to train in blind landing. Even if we limit ourselves only to simulators which have visual systems, those which appear in Table 5 differ notably in their visual characteristics, e.g., field of view $48^{\circ} \times 36^{\circ}$, $240^{\circ} \times 180^{\circ}$), scene content (i.e., model boards are fairly realistic, while computer-generated images resemble cartoons), and scope (model boards are limited to about 5 nmi x 15 nmi while CGI systems are virtually unlimited).

Nor is it correct to say that simulators with high fidelity motion systems save more flight time than devices without such systems. Current research results indicate that no differences can be found in the flight performances of pilots trained in simulators with or without motion (the studies have been limited to undergraduate pilots flying center-thrust aircraft and simulators equipped with wide-angle visual displays). In fact, the simulators in Table 5 differ in having 3 and 6 degrees of freedom and it is probably correct to say that not all of them have high-fidelity motion systems. Diehl and Ryan's observations are best regarded as suggestions, subject to verification, for establishing the ways in which simulators can be used most effectively. Simulators are training devices and we should expect that they are not equally effective for all types of training.

There is a wide range in the Transfer Effectiveness Ratios shown in Table 5. The TERs alone would help us identify the types of tasks for which any simulator may be a more (or less) effective training device than the aircraft itself. But additional information is needed to help us decide whether that simulator is also more (or less) cost effective than the aircraft for the particular type of training. Essentially, we have to compare the TER to the simulator/aircraft operating cost ratio per hour in order to decide whether to use the simulator or the aircraft for training purposes. Table 5 does not provide the cost data needed to make this type of decision. In interpreting these TERs, it is helpful to recall that most current simulator/aircraft operating cost ratios appear to be in the range of 0.10 to 0.20.

D. INCREMENTAL EFFECTIVENESS OF FLIGHT SIMULATORS

Although one continues to improve with additional training, the amount of improvement per hour or trial would be expected to decrease as training progresses. This is the phenomenon known as the learning curve (not to be confused with the production learning curve, which shows a similar trend). Thus, although it is convenient to calculate the TER over some portion of a training syllabus, the actual value can be expected to decrease with each additional hour or trial of training on a specific phase or level of skill acquisition. This implies that the effectiveness of a flight simulator as a training device would be greatest at the start of a given type of training and would decrease as that training proceeds. This is shown, with hypothetical data, in Figure 2. Despite diminishing training effectiveness, it is cost-effective to use the simulator up to the point where the TER equals or becomes less than the simulator/aircraft operating cost ratio. A discussion on the conditions for the efficient allocation of simulator and aircraft hours to training may be found in Volume II, Appendix A.[1] Obviously, it becomes important to establish

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(1) The incremental transfer effectiveness function and the product isoquants describe related but not identical relationships.

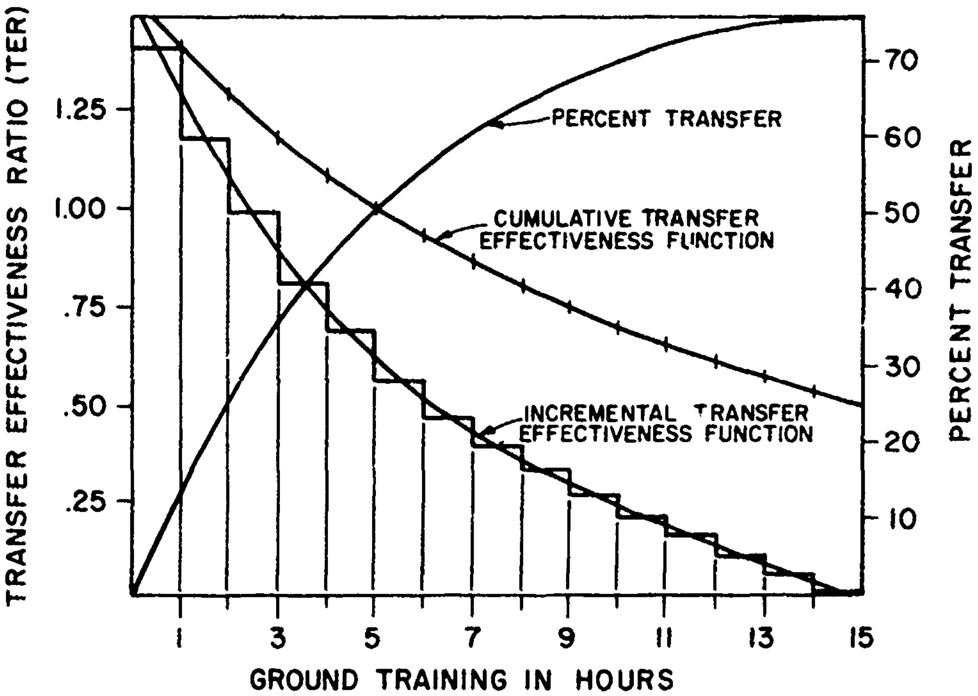


FIGURE 2. Relationships among transfer measures based on hypothetical data for general aviation ground trainers used in a ten-hour flight curriculum. (Source: Roscoe, 1971)

the shape of the learning curve so that one can determine the point beyond which further training on the simulator, although perhaps effective, is no longer cost-effective. Cost-effectiveness studies of this type are virtually nonexistent; an exception is the study of Povenmire and Roscoe (1973) reported in the next chapter, which determined the marginal productivity of a flight simulator by means of the Incremental Transfer Effectiveness Ratio. Thus, the demonstrated effectiveness of a flight simulator as a training device is a necessary but not a sufficient reason to justify its use, rather than that of the aircraft, for training. Obviously, we also need to know the simulator/aircraft operating cost ratio.

E. FIDELITY OF SIMULATION AND EFFECTIVENESS OF SIMULATORS

It is often assumed that improved fidelity increases the effectiveness of flight simulators for training purposes. The nature of this relationship is explained in Figure 3, where Johnson, Knight, and Sugarman (1975) repeat a figure used originally by Miller (1954). That training requires fidelity, particularly high fidelity, is a view popular with pilots and manufacturers of flight simulators. Since improved fidelity increases the cost and complexity of flight simulators, it is a subject which warrants discussion. Note that the beneficial effect of increased fidelity shown by Johnson et al is in the form of a hypothetical curve because little useful data on the relationship between fidelity and transfer have been developed since Miller's original paper.

"Fidelity" of simulation is generally not defined. Let us take it to mean the accuracy with which some feature or response characteristic of a simulator approaches the same feature of the aircraft; a more precise definition would distinguish between engineering and perceptual fidelity and propose ways of measuring them. We see immediately that fidelity is not a general characteristic of a simulator but that it applies separately to many of its details, e.g., the layout of instruments and controls in the cockpit, the nature of the aerodynamic flight equations and data processing that determine the movements of the instruments and the

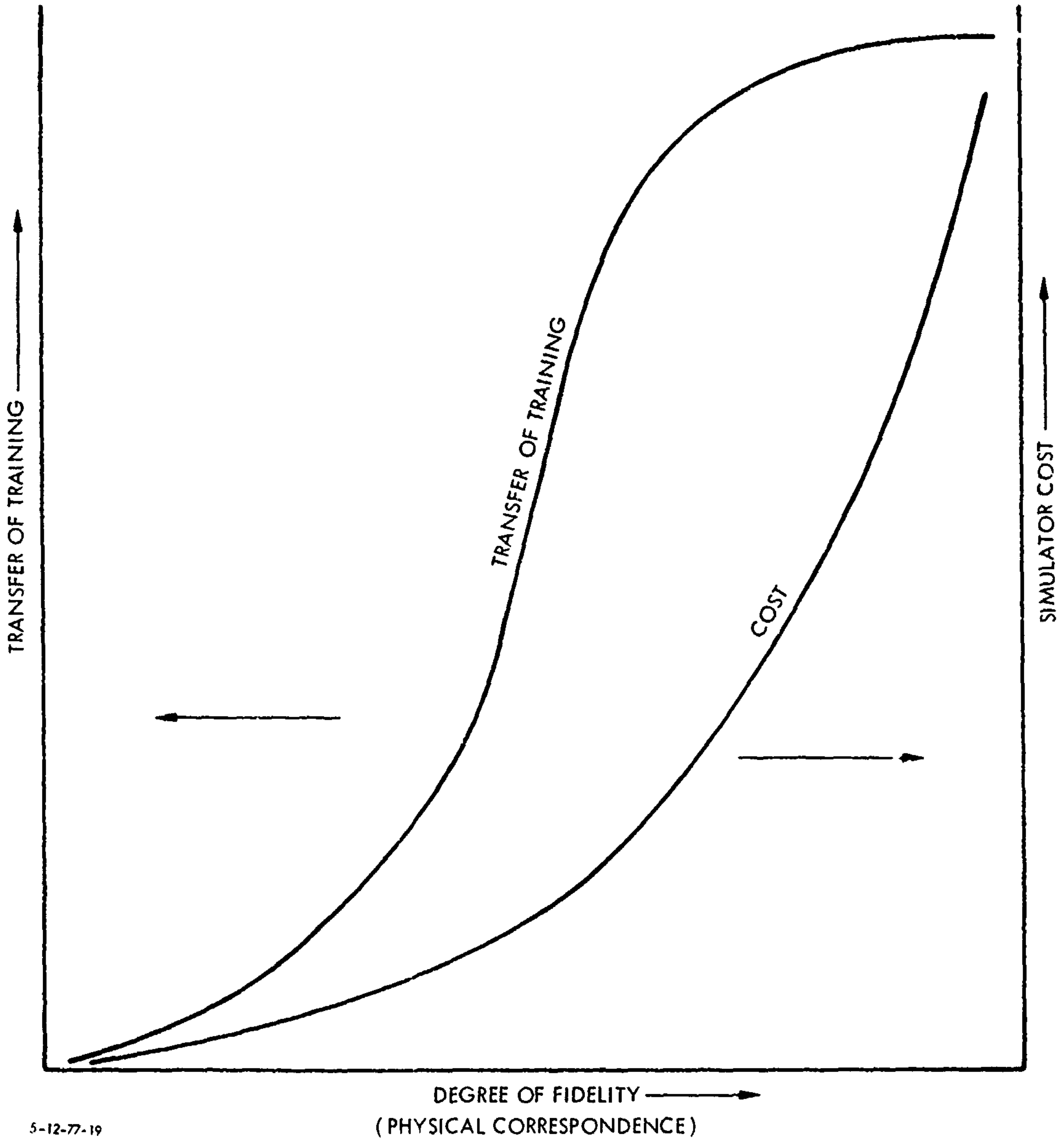


FIGURE 3. Cost, fidelity, transfer of training curves.
Source: Johnson, Knight and Sugarman (1975)

forces on the controls during various maneuvers, the visual and platform motion characteristics of the simulator, and so on. The type of fidelity needed in a simulator is obviously related to its intended use, e.g., vision is needed for training in landing and air-to-ground attack, but not in instrument flight. The required amount of fidelity is not, as yet, readily specifiable, e.g., 3 or 6 degrees of freedom in the motion base, size of the field of view and the need for color, rather than black and white, in the visual system.

There are two criteria that may be used to define the fidelity required in a flight simulator. One is the precision with which some real life characteristics of flight are duplicated, in engineering terms; the other is pilot acceptance or, more precisely, its perceptual equivalence to actual flight. It is reasonable to believe that improved fidelity of flight simulation should improve its training value. Pilots have clearly refused to accept simulators that have "poor" (i.e., nonrepresentative) handling qualities and simulator manufacturers have responded strongly to this demand. Thus, there has been a trend, both in development and procurement, to increase the fidelity of flight simulators. But, in fact, there has been insufficient research to examine which types of fidelity have demonstrable training value and which do not. The limits of this argument can easily be set. Prophet and Boyd (1970) found that a simple cockpit mock-up constructed of plywood and photographs, could be used to train a pilot in cockpit procedures just as well as a high fidelity trainer (Device 2-C-9) or the actual aircraft (the OV-1 Mohawk, a twin-engine turboprop Army aircraft). Dougherty, Houston, and Nicklas (1957) used devices, ranging in fidelity from photographic mock-up to the aircraft itself, to train pilots in flight procedures. They found that the higher fidelity devices produced better immediate transfer than the lower ones but the performance differences almost disappeared after five trials in the aircraft. Brown, Matheny, and

Flexman (1950) placed a perspective drawing of a runway on a blackboard in front of a Link trainer as an aid in teaching landings. The experimental group made fewer errors than the control group in learning to land a light aircraft. At the other extreme, some recent studies, discussed earlier, strongly suggest that pilots trained in a modern simulator without motion can perform acrobatics and other maneuvers in the air just as well as pilots trained with motion.

A motion base with six degrees of freedom, such as used, adds about $300,000 to the cost of a simulator and consumes over 100,000 watts of power. Too little is currently known about how much fidelity is actually needed for training. Clearly, fidelity of simulation deserves more careful examination than it has received to date, especially in view of the large procurements that are now being planned.

F. OVERVIEW

In summary, the effectiveness of flight simulators for training pilots has been demonstrated beyond doubt; no studies were found which might support a contrary finding. This conclusion is based largely on undergraduate pilot training using aircraft and simulators that are less advanced than those which are now becoming available. However, the conclusion is consistent with recent studies on modern simulators and there is no reason to believe that it will be altered. Factors that influence the effectiveness of simulators have received little systematic attention. It is important to learn more about the rate at which various types of training occur in simulators, i.e., the shape of the learning curves. The latter information is needed in order to determine when the rate of learning in the simulator reaches the point where it becomes more economical to accomplish additional training in the aircraft. There is also a need to determine the degree of fidelity required in a simulator for various types of military

training as well as the effect of various ways of using the simulator as a training device. The fact that simulators are effective for training does not necessarily imply that they do so economically or that they are cost-effective in that role.

IV. COST-EFFECTIVENESS OF FLIGHT SIMULATORS

There is no lack of knowledge concerning how to conduct a cost-effectiveness analysis of training (e.g., Duffy, Miller and Staley, 1977; Doughty, Stern, and Thompson, 1976; Broby, Henry, Parrish, and Swope, 1975; Spangenberg, Ribeck, and Moon, 1973; Swope, 1976; Swope and Cordell, 1976; Temkin, Connally, Marvin, Valdes, and Caviness, 1975; Toomepuu, 1977; Fisher, 1971). Volume II of this report considers in great detail how to estimate the costs of training in simulators and in aircraft. This was necessary because, as the rest of this chapter demonstrates, this knowledge has not been applied extensively to the use of flight simulators.

There are only a few studies on the cost-effectiveness of a flight simulator in actual use for some particular type of training. However, projections of cost-effectiveness, based on arbitrary assumptions of flight savings, and of simulator utilization appear in planning studies for the procurement of new flight simulators. Each of the few empirical studies found is described briefly below, with particular attention given to the form of the cost-effectiveness analysis.

A. Aircraft Cockpit Procedures Training, OV-1

The study by Prophet and Boyd (1970), noted above, approaches cost-effectiveness by comparing the effectiveness of three devices, differing widely in cost, for training pilots on selected ground cockpit procedures for the OV-1 aircraft. The three devices were:

Aircraft, OV-1
Cockpit procedures trainer, 2-C-9
Cockpit mock-up, constructed of plywood and photographs

The 2-C-9 trainer is a dynamic simulator with a high degree of physical fidelity. The locally constructed mock-up provides only rudimentary representation of the instruments and controls in the OV-1 cockpit. The subjects (10 per group, rated Army aviators with flight experience) were trained on procedures for pre-start, start, run-up, and shut-down in one of the three devices. Actual flight of the aircraft was not involved. After training, the ability of all subjects to perform 174 items on a checklist was measured in the airplane.

The main result was that all devices were equally effective for teaching OV-1 ground procedures. Cost data are not given, except that it cost about $35 in materials and 20 man-days of labor to construct the mock-up; presumably the mock-up, the 2-C-9 trainer, and the aircraft increase in cost, in that order. If this is correct, the mock-up would be the most cost-effective device for teaching ground procedures.

This study need not be regarded as a major contribution to the literature on the cost-effectiveness of flight simulators. It does not consider the possibility that use of the OV-1, despite its higher initial procurement cost, might require no additional training costs, as would the mock-up, if it was flown so little that it could also be used for procedure training on the ground. Still, it bears on the point that, depending on the task, it may be possible to demonstrate that a less expensive device can be as effective for some training purposes as a more expensive one with higher apparent fidelity. Similar findings have been demonstrated by Denenberg (1954) for teaching starting and stopping procedures in tanks, and by Cox et al (1965) for procedures training for the Nike Hercules missile system.

B. Hours Needed to Solo, Piper Cherokee

In this study, Povenmire and Roscoe (1973) were directly concerned with determining the cost-effectiveness of the Link GAT-1

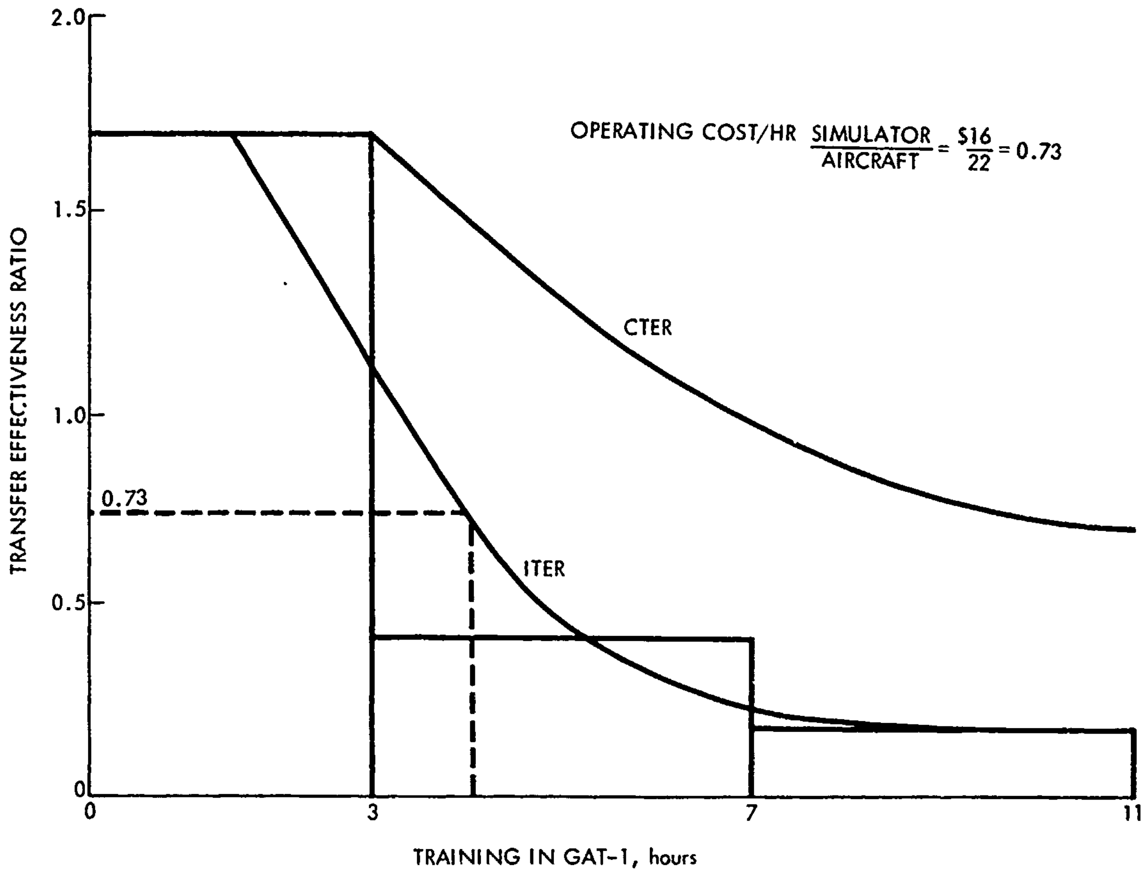
trainer to train student pilots to solo the Piper Cherokee, a primary flight trainer aircraft. The design of the experiment was to determine the Incremental Transfer Effectiveness Ratios for groups of student pilots given 0, 3, 7, or 11 hours of training in the simulator concurrently with flight instruction in the airplane.

The results, in Table 6, show that instruction in the simulator saved some flight time for each group, but additional hours after 3 hours in the simulator produced smaller savings in flight time. This is clearly demonstrated in Figure 4. The operating cost of the GAT-1 is $16 per hour and of the Piper Cherokee $22 per hour, including $8 for the instructor in each case. Therefore, training in the simulator is cost-effective until the Incremental Transfer Effectiveness Ratio drops below the ratio of simulator/aircraft operating cost per hour. The latter ratio is $16/22 = 0.73. Inspection of Figure 4 shows that for this study that point occurs between 4 and 5 hours in the GAT-1 for training student pilots to solo.

This excellently conceived study should serve as a model for determining the most cost-effective use of flight simulators for training.

TABLE 6. HOURS NEEDED TO PASS FINAL FLIGHT CHECK FOR STUDENT PILOTS GIVEN 0, 3, 7, or 11 HOURS OF INSTRUCTION IN THE LINK GAT-1 TRAINER

Group	N	Hours needed to solo (avg)	Flight time saved, hrs	CTER	ITER
Aircraft only	14	45.4	-	-	-
Simulator					
3 hrs	13	40.3	5.2	1.7	1.7
7 hrs	9	38.6	6.8	0.97	0.41
11 hrs	10	37.9	7.5	0.68	0.17



Source: POVENMIRE AND ROSCOE (1973)

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FIGURE 4. Incremental Transfer Effectiveness Ratio (ITER) and Operating Cost Ratio

C. Cockpit Motion, Piper Cherokee

The purpose of this study by Jacobs and Roscoe (1975) was to determine the effect of cockpit motion in a simulator on the training of student pilots. The Link GAT-2 simulator provides motion in pitch and bank; the aircraft was the Piper Cherokee Arrow. The experiment involved training student pilots (9 per group) under one of the following conditions:

Airplane only

Normal washout:	Simulator with normal cockpit motion (bank motions followed by below threshold washout; sustained pitch angles)
Fixed base:	No simulator motion
Random washout:	Normal onset and acceleration cues in bank but direction of motion reversed randomly 50 percent of the time; sub-threshold washout, as above; normal sustained pitch angles.

Performance of all groups was measured on 11 flight maneuvers in the Private Pilot Flight Curriculum, according to FAA standards. The experimental results are shown in Table 7 and a cost analysis is shown in Table 8.

Training in the simulator saved some flight time for each experimental group. Training with normal banking motion and washout saved about the same amount of flight time as training without motion. Both of these saved more time than training with random banking motion and washout but even the latter group saved some flight time. A striking finding is that no subject in the latter group commented on the strange nature of the randomly reversed motion during training or when questioned specifically after the experiment. Perception of motion is not precise and experience with uncoordinated motion forces can only be gained in a flight or similar environment. Thus, it may be that a trainee, with little to guide him, cannot distinguish between random or representative motion.

TABLE 7. SUMMARY OF OVERALL FLIGHT TIME SAVINGS IN MINUTES AND TRANSFER EFFECTIVENESS RATIO AS A FUNCTION OF SIMULATOR COCKPIT MOTION CONDITIONS

Experimental Group	Time in Minutes: Flight Time	Flight Time Saved	GAT-2 Time	Transfer Effectiveness Ratio
Airplane Only	387	-	-	-
Normal Washout	248	139	442	0.314
Fixed Base	255	132	442	0.299
Random Washout	280	107	429	0.250

Source: Jacobs and Roscoe, 1975

TABLE 8. ANALYSIS OF COSTS FOR USE OF AIRPLANE AND SIMULATORS SHOWN IN TABLE 7

Group	Cost/ hr*	Airplane: Flight Time Saved, hrs	Airplane: Flight Costs Avoided	Simulator: Time Used, hrs	Simulator: Cost	Cost Savings Aircraft-Simulator†
Airplane	$28.00	-	-	-	-	-
Normal Washout	15.30	2.32	64.96	7.37	$112.76	-$47.80
Fixed-Base	10.60	2.20	61.60	7.37	78.12	- 16.52
Random Washout	15.30	1.78	49.84	7.15	109.40	- 59.56

* Including instructor

** Control: This group used the airplane 6.45 hours at a cost of $180.60

† Negative values indicate additional cost rather than savings

Source: Jacobs and Roscoe, 1975

The cost analysis appears to indicate that the airplane is more cost-effective than any of the simulator conditions, fixed or moving, in this experiment. Among the simulator conditions, the fixed base version is most cost-effective (least cost-ineffective). Due to the design of the experiment, the amount of time spent in the simulator was arbitrarily fixed and some student-pilots may have been trained on the simulator beyond the point of efficiency, i.e., where the ratio of the simulator/aircraft operating cost exceeded the ITER of the simulator. If a criterion based on the simulator/aircraft cost ratio had been followed, use of the simulator should have been stopped at slightly less than 1 hour for the moving base group and at slightly less than 2 hours for fixed-base simulator group. Up to these points, use of the simulator for training would have been more cost-effective than the airplane.

D. Helicopter Training, HH-52A and HH-3F

This study by Isley, Corley, and Caro (1974) estimates the cost benefits of an advanced flight simulator and an improved syllabus for training helicopter pilots in the Coast Guard compared to the period before the simulators were introduced. Effectiveness is estimated by the number of simulator and flight hours needed to qualify pilots in the new program compared to flight hours alone in the earlier program. No experiment was performed. Since an improved training program, based on specified behavioral objectives and proficiency based advancement was introduced together with the simulator, it is not possible to determine what portion of the benefits can be attributed only to the simulator. The VCTS (variable cockpit training system) can simulate both the HH-52A and HH-3F helicopters; it has a motion base with 6 degrees of freedom, but no visual system.

Introduction of the simulator (and the improved training program) reduced flight hours and produced the savings shown in Table 9. Operating costs of the simulator are much less than those of the two helicopters ($59 per hour vs $504 and $815). Proficiency training is now accomplished solely in the simulator. The simulator cost $3100K to procure. Realized benefits are estimated at $1454K per year, plus estimated benefits of $1082K per year due to reduced flight time in preparation for check rides. Thus, depending on which estimate of benefits is used, the investment can be amortized in 1.2 or 2.1 years. The required level of flight proficiency was not changed. Savings of nearly $1M per year for 1974-1976 are noted in a more recent report on this program. (Povenmire, Russell, and Schmidt, 1977).

E. Anti-Submarine Warfare, P-3C

This study, by Browning, Ryan, Scott, and Smode (1977) compares the cost and effectiveness of two programs for transition training of Naval pilots to fly the P-3C, a four-engine turboprop aircraft used in anti-submarine warfare. The current program uses the 2F87F

TABLE 9. COMPARISON OF COSTS TO TRAIN HELICOPTER PILOTS IN THE COAST GUARD BEFORE AND AFTER THE INTRODUCTION OF THE VCTS SIMULATOR. (1974 DOLLARS IN BOTH CASES). DATA FROM ISLEY, CORLEY AND CARO (1974)

			Before		After				
		No. of Pilots/yr.	Flight hrs.[1]	Costs (000)[2]	Flight hrs.[3]	Simulator hrs.[4]	TER[5]	Costs (000)[2]	Benefits (000)
Realized Benefits									
HH52A	Transition	30	31	$ 469	28	9	0.33	$ 439	$ 30
	Qualification	18	78	708	36	11	3.82	338	370
	Proficiency	300	3	454	0	6	0.50	106	348
HH3F	Transition	32	36	939	23	15	0.87	628	311
	Proficiency	200	3	489	0	8	0.38	94	395
	Totals	580		$3059				$1605	$1454
Estimated Benefits[6]									
HH52A	Proficiency	300	3	454	0	3	1.00	53	401
HH3F	Proficiency	200	4.5	734	0	4.5	1.00	53	681
	Totals	500		$1188				$ 106	$1082

[1]Required

[2]Operating costs per hour, 1974 dollars: Aircraft HH52A $504
HH3F 815
Simulator 59

Aircraft costs include programmed utilization of 600 hrs/yr for HH52A, 700 hrs/yr for HH3F, and prorated overhaul, spares, maintenance, ground support, crew, fuel, lubricants.

Simulator costs (average of two simulators) include 75 percent utilization for 12 hrs x 5 days x 48 weeks and field maintenance, spare parts, utilities, staff, instructors and student travel.

Amortization costs are excluded

[3]Actual
[4]Actual (mean, pilot, and co-pilot)
[5]Derived from data in report
[6]Potential savings from use of simulator instead of aircraft in preparation for check ride and emergency procedures test.

simulator, an experimental syllabus and the P-3C aircraft; the previous program used the 2F69D simulator, a "standard" syllabus and the P-3A/B aircraft. There were 27 pilots in the experimental and 16 in the control group; data from 58 pilots in previous classes were used as another control group. All pilots had completed undergraduate multi-engine training in the S-2, a small, two-engine propeller-driven aircraft. All were newly designated first-tour naval aviators and possessed Standard Instrument Cards. After training, performance was measured in the aircraft on 20 of the 45 tasks in the Familiarization and Instrument phase of transition training. The critical data were the flight hours required by each group to perform these tasks in a proficient (i.e., acceptable) manner.

The following devices were used by subjects in the study:

- Cockpit Familiarization Trainer (CFT) Device 2C23A. Provides training in nomenclature, location and function of controls, instruments, switches, lights.
- Cockpit Procedures Trainer (CPT) Device 2C45. Provides training in powerplant management and systems procedures for normal and emergency operations (actually an obsolete P-3 operational flight trainer with flight dynamics, motion, and unneeded systems removed).
- Operational Flight Trainer (OFT) Device 2F69D. Provides crew or individual training for pilot, copilot, and flight engineer. This OFT is a solid state analog device (1966 era) which simulates flight dynamics, systems, navigation, and communications for P-3A/B aircraft. It provides motion with 3 degrees of freedom, but no visual simulation.

- Operational Flight Trainer (OFT) Device 2F87F
  Recently accepted, this is a digital device which simulates the P-3C Orion aircraft. It provides motion with 6 degrees of freedom and vision (50° wide x 38° high) by means of a TV model board system (15 nmi x 5 nmi) for low-altitude maneuvers such as takeoff, landing, and instrument approaches. It replaces the 2F69D.

There was no difference between the experimental and control groups concerning their flight proficiency as measured in the aircraft after training in the simulators, as described above. The basic results, in terms of simulator and flight hours required to achieve this proficiency, and the related cost data, are shown in Table 10. Compared to the earlier program, the major finding was that additional hours with the new syllabus in the new simulator (24 vs 9) can reduce the hours required in the aircraft to achieve acceptable performance (9 vs 15). Since it costs more to operate the aircraft than the new simulator ($2284 vs $144 per hour), the new program will cost less than the previous one, even though it offers more total training hours per student (49 vs 37). The crucial aspects, of course, are the improved curriculum and the increased use of the improved simulator for training. The difference in operating cost per hour of the old and new simulators is trivial, i.e., $10 per hour.

The new simulator costs $4.2 million to procure while the old one cost $1.4 million. Given that the annual operating cost of the new program is $2.5M less than the previous one, the cost of the new simulator would be amortized in less than 2 years (the estimate does not include the cost of developing the improved syllabus). The table also shows that fewer aircraft will now be needed to train pilots and that the total investment cost of the new program is $63 million, compared to $99 million for the previous one. An analysis in the paper shows that the life-cycle costs of the two programs over a 10-year period, at discounted rates in

TABLE 10. HOURS IN SIMULATORS AND AIRCRAFT REQUIRED TO ACHIEVE PROFICIENCY IN THE AIRCRAFT, OPERATING COSTS PER HOUR, ANNUAL AND PROGRAM COSTS PER HOUR, ANNUAL AND PROGRAM COSTS FOR TWO P-3C TRAINING PROGRAMS. (PROJECTIONS BASED ON TRAINING 200 PILOTS PER YEAR) SOURCE: BROWNING, RYAN, SCOTT AND SMODE (1977)

Device	Hours Required Per Student	Total Device, hrs/year*	Operating Cost/hr**	Total Cost/yr**	No. of Devices Needed	Present Value (each)	Total Investment (present value)
Control Group (N-16)							
CPT (2C45)	13	1300	$ 104	$ 135K	1	$1390K	$1390K
OFT (2F69D)	9	900	134	121	1	1396	1396
P-3C	15	3000	2284	6853	7	13700	95900
Total	37	5200	$2522	$7109K			$98686K
Experimental Group (N-27)							
CPT (2C45)	16	1600	104	166K	1	1390	1390
OFT (2F87F)	24	2400	144	346	1	4225	4225
P-3C	9	1800	2284	4112	4.2	13700	57540
Total	49	5800	$2532	$4624K			$63155K

*For 200 pilots/yr

**Includes maintenance and support costs of two students and one instructor; availability of devices assumed as shown (P-3C hours based on actual utilization):

CPT 3000 hrs per yr (12 x 5 x 50)
2F69D 3000 hrs per yr (12 x 5 x 50)
2F87F 4000 hrs per yr (16 x 5 x 50
P-3C 428 hrs per yr (35.7 x 12)

accordance with DoD Instruction 7041.3, would be $81M for the new program compared to $125M for the previous one, a savings of $40M.

In this analysis, the operating cost of the P-3C is given as $2284 per hour. According to the Navy Aircraft Program Data File, (January 1977) the operating cost of the P-3C is given as $602 per hour (this report, Appendix A). If the latter figure is used in the analysis, the savings per year for the new program would be $467K instead of $2485K and the procurement cost of the 2F87F simulator would be amortized in 9 rather than 2 years. We are not able, at the time of writing this report, to explain the reasons for the wide difference between the two values for the operating cost of the P-3C. The discrepancy in the two estimates strongly points to the need for reliable data for use in analyses of training costs.

The average number of landings needed to establish proficiency in the experimental group was 36 per pilot; in the control group it was 52. Presumably, the savings in flight time on this account could be related to the cost of adding a visual system to the new simulator (lacking in the old one), but an analysis of the cost-effectiveness of this feature was not made. Future studies on the program will (1) determine substitution ratios through comparison of groups trained only in the aircraft with those trained with the simulator, (2) study the contribution of motion to simulator training, (3) and evaluate a strategy based on training pilots to established proficiency standards for specified tasks, rather than on allocating a predetermined number of hours in the simulator and the aircraft. The latter requires developing performance standards and using a presently unused measuring capability of the 2F87F.

F. Airline Use of Flight Simulators

The airlines are often cited as a model for the use of flight simulators to train and check flight crews, a procedure which has been approved by the FAA. The procurement of simulators by the airlines probably influenced the improvement of these devices,

especially when the military services did not provide a large market. At present, some airlines operate 10 to 12 simulators.

One might assume that the airline use of flight simulators indicates their cost-effectiveness for training, although precise information to this effect has not been published. However, it is possible to construct a general estimate based on information published primarily by American Airlines. It is assumed that all airlines follow similar procedures because they must comply with training standards set by the FAA; also, they cooperate to establish a training program.

Figure 5 shows the reduction in the number of hours in the simulator and the aircraft for transition training of pilots by American Airlines on four aircraft over the period 1967-1975 (Melden and Houston, 1975). Transition training is the qualification of a pilot or co-pilot for the same crew position on another type of aircraft. Using transition training to the B-707 from 1968 to 1975 as an example, use of the simulator decreased from 27 to 19 hours, while use of the aircraft decreased from 12.5 to about 1.5 hours. For the DC-10, which was introduced later, simulator and aircraft time declined by smaller amounts from their initial levels to the present values of about 19 and 1.7 hours, respectively. Table 11 shows the trend towards reduction of simulator and aircraft hours, as well as the operating cost of these devices. Using these data, and information published by the Civil Aeronautics Board, the cost of aircraft and simulator time for training a captain is estimated in Table 12.

These results can be regarded as suggestive only, since the sources on which they are based did not necessarily use the same assumptions. Nevertheless, they do suggest that the costs of training a transitioning captain are now about 30 to 80 percent of their earlier values, depending on which airplane is used for this comparison. (The median value is about 40 percent.) This finding is consistent with Figure 6 provided by American Airlines

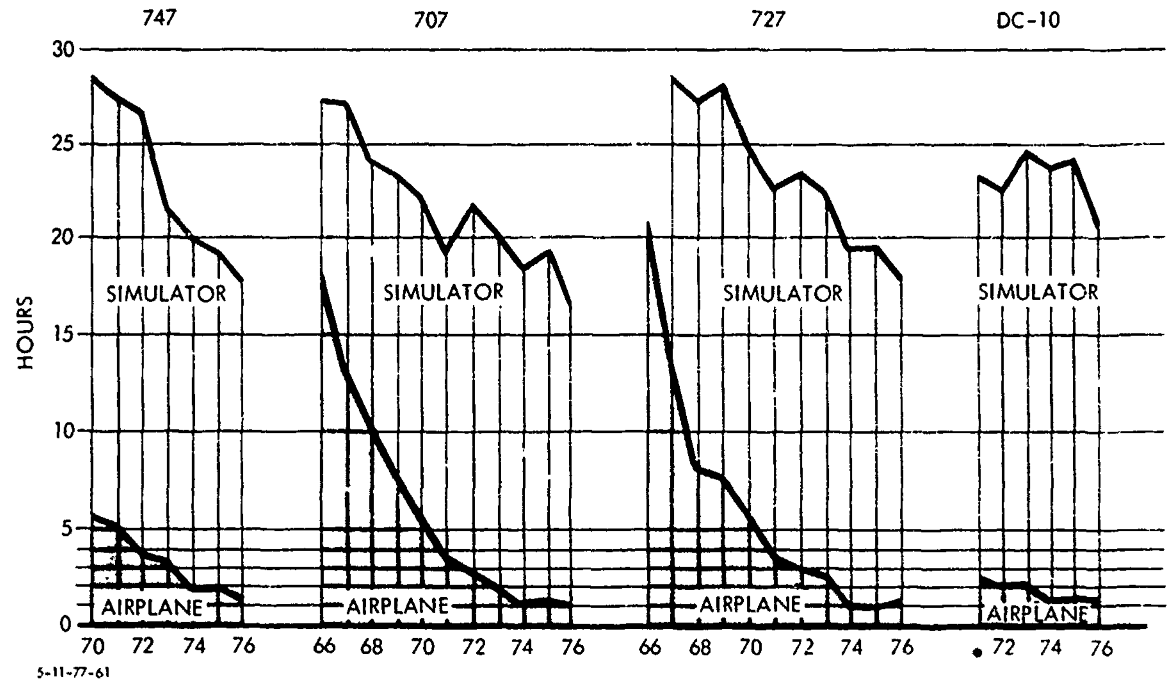

FIGURE 5. Average hours of training in simulator and airplane for Captains in transition training, American Airlines (provided by Robert C. Houston, Director, Training Support, American Airlines)

TABLE 11. AVERAGE TRAINING HOURS IN SIMULATOR AND AIRCRAFT FOR CAPTAIN TRANSITION PROGRAMS*

Aircraft	Original Period	Original Period, hrs Aircraft	Original Period, hrs Simulator	1974 hrs Aircraft	1974 hrs Simulator	Operating cost/hr, 1975 Aircraft	Operating cost/hr, 1975 Simulator
B-747	1970	5.5	28	2.0	19	$2358	$ 275
B-707	1967	12.5	27	1.3	19	935	213
B-727	1967	12.0	28.5	1.3	19	735	140
DC-10	1971	2.2	23	1.7	19	1341	175

*Simulator and aircraft hours by inspection of Figure 5; aircraft cost data from "Aircraft Operating Cost and Performance Report for Calendar Years 1974 and 1975", Civil Aeronautics Board July 1976; simulator cost data from sev- -l private sources Crew expenses are not included

TABLE 12. COST ESTIMATE OF AIRPLANE-AND-SIMULATOR TIME FOR CAPTAINS IN TRANSITION TRAINING IN 1974 AND AN EARLIER PERIOD (DATA FROM TABLE 11)

	Original Period		1974	1974 Costs as Percentage of Original Cost
B-747	1970	$20,669	$9,941	48
B-707	1967	17,439	5,263	30
B-727	1967	12,810	3,616	28
DC-10	1971	6,975	5,605	80

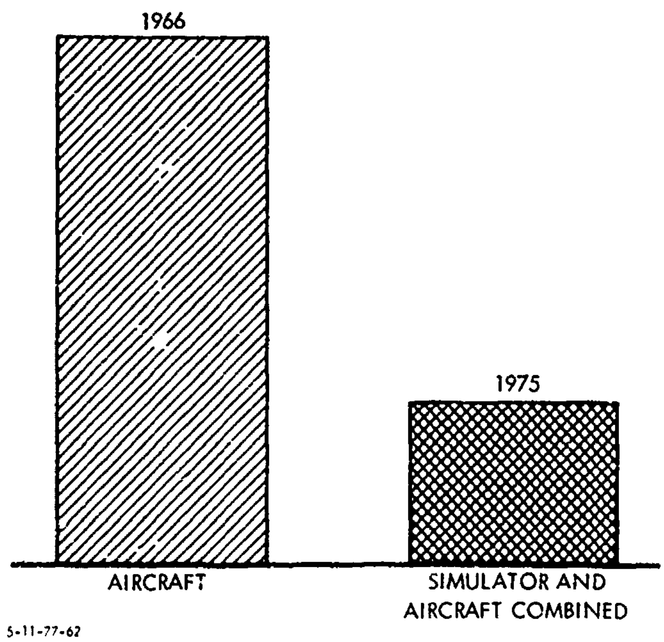

FIGURE 6. Comparison of costs at American Airlines for transition training of captains for the B-727 using only aircraft (1966) or simulator and aircraft (1975); 1975 dollars in both cases. Original figure does not contain scale for dollars. (Source: American Airlines)

which compares the cost of transition flight training for the captain of a B-727 with the aircraft alone in 1966 or with the simulator-and-aircraft in 1975. Both estimates are based on 1975 dollars. Note, however, that no dollar scale is provided. Using a ruler to measure the height of the bars, we estimate that training with simulator-and-aircraft in 1975 cost American Airlines 31 percent of what it cost using only aircraft in 1966.

The reduction in aircraft time shown in Figure 5 cannot be attributed primarily to the introduction of flight simulators, since the latter were in use throughout the period. Presumably, the reduction in aircraft hours must be related in some way to how the simulators were being used. Information published by American Airlines helps explain what happened. In 1966, American Airlines replaced several operating bases with centralized training at one location. Standard procedures were developed and, for the first time, enforced for use in flight and, obviously, in training. Specific performance objectives were established to define the skills to be trained. Training in these skills was sequenced in an order to promote efficient learning. Pilots were trained to proficiency, i.e., to achieve specified performance standards at their own pace rather than to complete their training with predetermined time limits. Particular lessons in the curriculum were assigned to the classroom, or to cockpit procedure trainers, or to individual learning by means of audio-visual cassettes as well as, of course, to the simulator and the aircraft. Appropriate sequencing of these lessons, as well as accomplishment of each lesson by the least expensive but acceptable means accounts, in general, for reductions both in simulator and in aircraft time. Some of the improvement is attributed also to improved handling characteristics of the simulators on landing. Since the simulators did not appear to perform landing maneuvers in a realistic manner, the airline was required to collect flight dynamics data not previously available. Thus, improvements were made to all aspects of the training program and not only to the flight simulator portion.

The current use of flight simulators by American Airlines appears to be cost-effective. Training costs were reduced to levels that appear to be 30-80 percent of what they were before training was centralized and improved. Simulators were given greater emphasis and their hours of use declined somewhat; a greater decrease in aircraft hours accounts for most of the savings. Training is judged to be effective according to the criterion that it meets FAA standards, as did the previous program. American Airlines claims that the new training program is more effective than the previous one because the safety record has improved and there is greater crew compliance with specified operating procedures. A major lesson from this experience must be that the way in which the flight simulator and other training facilities are used is at least as important as whether or not the simulator is used at all.

One airline, which will not be identified, provided an analysis concerning the cost-effectiveness of its training program for the year 1976. The data in Table 13 represents the use of simulators and aircraft for all training purposes, i.e., transition, upgrading, and periodic requalification; aircraft types are not named so as not to identify the airline. The analysis is based on the assumption that, if a simulator was not available, each simulator training hour would have been performed in the aircraft. The number of days needed for training would be the same, regardless of whether training was accomplished in an aircraft or in a simulator and, therefore, with no impact on travel and incidental costs. Fully allocated costs of simulators and aircraft are used in the analysis. The analysis is conservative because it does not include the cost of delays due to weather or to the scheduling of aircraft.

The use of simulator and aircraft costs this airline 21 percent of what it would cost if only aircraft were used in the training program. The saving is estimated to be $25 million in 1 year

TABLE 13. HOURS SPENT IN TRAINING IN SIMULATORS AND AIRCRAFT AND COST COMPARISON FOR ONE AIRLINE, 1976

Aircraft	Simulator Hours	Aircraft Hours	Total Hours
A	3,511.8	185.7	3,697.5
B	8,996.8	272.3	9,269.1
C	12,277.6	547.2	12,824.8
D	1,262.1	117.5	1,379.6
Total	26,048.3	1,122.7	27,171.0

COST COMPARISON

Aircraft	Simulator and Aircraft	Aircraft Only	Simulator and Aircraft as Percentage of Aircraft-Only Costs
A	$1,159,922	$ 5,964,068	19
B	2,093,150	10,613,119	20
C	2,909,287	11,785,991	25
D	635,618	3,654,560	17
Total	$6,797,977	$32,017,738	21

and the procurement cost of the simulators ($17.5 million) can be amortized in less than 9 months. In fact, the cost of the entire training facility can be amortized in less than 2 years.

These results are significant, but they cannot be used as a standard for military training. The airlines are concerned only with highly experienced pilots who are permitted to fly 80 hours per month (the current average is about 50). The military must train undergraduate pilots and maintain the combat skills of graduate pilots who, on the average, fly 100 to 200 hours per year. It is also obvious that, except for transport type aircraft, the airlines and the military services perform different missions and maneuvers and use different aircraft and simulators. Although flight simulation offers significant advantages to the airlines and to the military services, direct comparisons of the costs and of the effectiveness of simulators for these users should not be made without full consideration of the differences in the two applications.

G. Current Studies of Cost-Effectiveness of Flight Simulators

More studies on the cost-effectiveness of flight simulators are now being conducted or planned than were completed over the last 10 to 20 years. Only current studies are really applicable to the new simulators, revised syllabi, and the modern performance measurement and instructional strategies that are replacing our previous concepts of flight training. The following efforts are worthy of note.

a. Test and evaluation of the Army's CH-47 Helicopter flight simulator. The CH-47 Flight Simulator (2B31) is a new device which provides motion with 6 degrees of freedom and a visual system based on a terrain model board viewed by a TV camera. Its evaluation, at the US Army Aviation Center, Fort Rucker, includes a combined development and operational test (DT/OT II) conducted by the US Army Aviation Board and a Cost and Training Effectiveness Analysis (CTEA) conducted by the Deputy Chief of Staff for Combat Developments Study Group of the Aviation Center.

Transfer of training will be measured for control (aircraft) and experimental (simulator) pilots in the CH-47 Qualification Course (called "institutional training"). Transfer will also be measured in subsequent unit training for pilots who will maintain their skills by training only in the simulator, or only in the CH-47, or with a mix of the two. Using data developed by the tests, cost and effectiveness analyses will be made of each option available for pilot training. The procurement of flight simulators will be based on the results of this analysis. The time frame for this study is January-October 1977. (Toomepuu, 1977)

Preliminary data on the first four pilots to complete transition training in this program are summarized in Table 14. The initial findings are that the experimental pilots can accomplish their check ride after 17 hours in the simulator and 17 hours in the helicopter compared to a control group that required 27 hours when trained solely in the helicopter. The experimental group received a higher average grade than the control group on the check flight (86 compared to 81) and the cost of transition training was reduced by $8412 per pilot.

TABLE 14. AVERAGE TIME REQUIRED TO ACCOMPLISH CHECK RIDE FOR TWO GROUPS OF PILOTS: PRELIMINARY DATA

Group	N	Average Score on Check Ride	Hours Required for Check Ride, Simulator	Hours Required for Check Ride, Aircraft	Cost/ Pilot*
Control	-	81	-	27	$27,027
Experimental	4	86	17	17	18,615
			Savings per pilot		$8,412

*Based on operating cost per hour of $1001 for the CH-47 helicopter and $94 for the 2B31 flight simulator.

Source: Aviation Systems Division - Army DCS/RDA, Weekly Summary, 4-8 April 1977

b. Simulator Training Requirements Effectiveness Study (STRES)

The purpose of this program is to determine the cost and effectiveness of major features of flight simulators for use in training. The method is to collect and evaluate historical data, including some from current training programs of the three services and the airlines. Attention will be given to determining the degree of fidelity necessary to achieve specific training objectives, the most effective ways of using flight simulators, and the most effective types of instructional features for such devices. An effort will also be made to identify the factors that influence the costs of ownership of flight simulators. The first phase of this study, which was to develop a methodology and plan of work, has been completed. It appears that the worth of simulators should be assessed not only in savings attributed to reduced flying hours but, if possible, in savings attributed to their influence on safety and accident rates, life-cycle costs, acquisition dollars in relation to flying hour avoidance and extended useful lifetimes for the aircraft. The study, which is being conducted by the Air Force Human Resources Laboratory, Advanced Systems Division, with the assistance of a tri-service management team, is scheduled for completion by December 1978. (AFHRL-ASD Project No. 1710-03-42, PE 62205 F, 25 Aug. 1976).

c. Other Studies

Other known studies are cited by title alone (the list may not be complete):

Cost Analysis of Visual Motion Systems of ASPT.
AFHRL-FTD 1123-03-31

Development of Life Cycle Cost Analysis Methods.
AFHRL-FTD 1123-02-66

Cost Effectiveness Methodology for Aircrew Training Devices.
AFHRL-FTD 1192-05-03

Development of USAF Military Personnel Costing Techniques for Use in Weapon System Design.
AFHRL-ASD 1124-03-06

Life Cycle Cost of Simulated vs Actual Avionic Maintenance Equipment for the F-16 Training Program.
AFHRL-ASD 1710-03-04

Simulator Capabilities Assessment Study.
AFSC-ASD-SD-24 Simulator System Program Office

H. Discussion

Only two studies were found which relate directly to the cost-effectiveness of modern flight simulators for use by the military in flight training. Browning, Ryan, Scott, and Smode (1977) report that the cost of the 2F87F, a new simulator, can be amortized in less than 2 years. The 2F87F is being used for transition training of about 200 Naval pilots a year to fly the P-3C, an aircraft used in anti-submarine warfare. Isley, Corley, and Caro (1974) show that the cost of the VCTS, another new simulator, can be amortized in 2 years or less. The VCTS is being used for transition and proficiency training of about 500 Coast Guard pilots a year to fly the HH-52A and HH-3F helicopters used in air/sea rescue. Of course, the Coast Guard is not a military service, but its training and proficiency program may be regarded as similar, in selected areas, to that of the military services.

These amortization periods, based on actual training programs, are less than an estimate of 4.8 years provided by the DoD to the Congress (DoD Report on Flight Simulation to the Senate Armed Services Committee, February 1977) This is the median value of the amortization periods for 97 units of 24 different flight simulators authorized or requested during FY 1976-FY 1978. The value of 4.8 years assumes a 6 percent discount rate over the pay-back period; it would be 3.8 years if no discount is assumed.

Although the information and analyses available to us are quite limited, it appears that an airline might be able to amortize its investment in flight simulators for transition and proficiency training on commercial aircraft within one year.

Povenmire and Roscoe (1973) and Jacobs and Roscoe (1975) show

that the cost-effectiveness of a flight simulator for training purposes is greater during the earlier rather than during the later stages of training on the tasks that were studied. This is simply the result that the rate of learning on the simulator decreases with additional practice, i.e., the learning curve. The cross-over point for cost-effectiveness of the simulator occurs when the incremental transfer effectiveness ratio (ITER, the amount of additional learning per unit time in the simulator) becomes less than the simulator/aircraft operating cost ratio. Although these two reports by Roscoe and his co-authors are based only on student pilots using simple simulators while learning to fly private aircraft (Piper Cherokee), there is no reason to anticipate different results with the more complex simulators and aircraft used by the military services.

The finding that flight simulators are cost-effective for the P-3C, HH-52A and HH-3F, and the airlines, is based on analyses of entire training programs or, at least, on large segments of training programs. General knowledge about learning curves, as well as the findings in the two studies which report ITER's, suggest that the cost-effectiveness of flight simulators could be optimized within training programs, provided information was available on rates of learning various tasks in the flight training syllabus. This information is needed to determine when additional training is better given, on cost-effectiveness grounds, in the aircraft rather than in the simulator. Such information is not currently available. Its collection on a systematic basis is desirable and probably necessary, in the long run, to control training costs, although it is not suggested that it would be a trivial undertaking to collect the necessary data.

V. IMPROVEMENT OF FLIGHT SIMULATORS

A modern flight simulator can include many subsystems, such as the basic cockpit and data-processing equipment required to represent a wide range of flight conditions, a motion platform, a visual display which represents the outside world, and a instructor's console, with some performance measurement and flight demonstration capabilities. At present, major research and development activities for the improvement of flight simulators center on the motion and visual subsystems.

Almost all flight simulators procured recently or planned for procurement by the DoD have motion and visual systems. Visual systems will be retrofitted into some simulators which now lack them. In a recent survey, 16 domestic airlines reported that they own 70 simulators, only two of which lack motion; all have visual systems. (Killian 1977). Many foreign airlines not included in the survey are also known to operate simulators with visual and motion systems.

Early simulators provided platform motion, but it was of such poor quality that it was abandoned. Many flight simulators built 10 or more years ago did not have motion and visual systems and were used primarily for training in instrument flight procedures, navigation, and radar. Improved motion and visual systems tended to make flight simulators more acceptable to pilots, particularly in the case of the airlines. Simulators with motion and visual systems are intended for use in training on such tasks as takeoff and landing, air-combat maneuvering, air-to-ground attack, carrier landing, formation flying, aerial refuelling, and nap-of-the-earth flight in helicopters.

Typical current costs for the major components of flight simulators are shown in Table 15. It will be seen that a basic flight simulator, including the data processing needed to drive the instruments and dynamic controls, costs about $2M. Platform motion adds $0.2M to $0.5M to this cost; the motion system for a fighter is more expensive than one for a wide-bodied aircraft, since it needs a larger and heavier visual system and maneuvers more violently. Additional military construction needed to accommodate a motion base is estimated to cost $30K; operation and maintenance is estimated at $30-35K per year. The 10-year life-cycle cost of a motion base is estimated to add $530K-$580K to the total cost of a wide-bodied aircraft flight simulator and $830K-$880K to that of a fighter (Cost Analysis, 1976). Visual systems might add from $0.3M to $4.5M to the basic cost, depending on the complexity of the display; the cost will be larger if the simulator requires two cockpits; life-cycle cost data were not available for visual systems.

A. Motion Systems

The need for motion in flight simulators has been questioned seriously on the basis of a recent research finding. The cost of simulators has also been questioned. The research finding is that pilots perform equally well in aircraft whether trained in simulators with or without platform motion. Major Jefferson M. Koonce, USAF (1974) working with Stanley N. Roscoe at the University of Illinois at Urbana-Champaign, studied the effect of transfer of refresher training in instrument skills from a Link GAT-2 simulator to a Piper Aztec airplane. All subjects (10 per group) were instrument pilots trained identically in the simulator in one of three ways:

- No motion
- Sustained banking and pitching motion
- Subliminal washout of banked attitudes during turns.

The GAT-2 provides motion with 2 degrees of freedom: bank and pitch. Banking in order to turn an aircraft produces a rotational

TABLE 15. TYPICAL PROCUREMENT COSTS FOR MAJOR COMPONENTS OF CURRENT FLIGHT SIMULATORS. SOURCE: SIMULATOR SYSTEMS PROGRAM OFFICE, ASD AFSC, MARCH 1977

			Examples*
Cockpit		$2 M	F-5
Functional Systems			
Dynamic Control Loading			
Flight and Navigation Instrumentation			
Some Weapons Functions			
Motion Cueing			
Fighter 6 DOF		0.5	
Wide body 6 DOF		0.2	
G-suit, G-seat, Buffet		0.2	
Visual Systems			
Dome Systems		3.3	
two domes	0.3		
sky-earth projectors	0.4		
missile projectors	-		
eight target projectors	0.3		
target generation	2.3		
Dual dome, Computer Image Generator		3.3	Air-to-Ground, F-15
Duoview (1 window, 1 channel)		1.4	KC-135
Night only, CGI (1 window, 1 channel)		0.3	EF-111A
Night only, CGI (3 windows, 3 channels)		0.4	EF-111A
Day-night Image Generation (3 windows, 3 channels)		1.3	EF-111A
Dual Fighter/Attack		4.5	Air-to-Surface Air-to-Ground ASPT, F-16
Double ASPT CGI		6.2	
Terrain Model Board		1.8	UPT-IFS**
Night-only CGI		1.8	UPT-IFS**
Day and Night CGI .		3.3	UPT-IFS**
Sensors			
Air-to-Air Radar		0.4	
Digital Radar Landmass		2.8	EF-111A
Instructional Features			
Engagement Display		0.3	
Automated Demonstrations		0.1	
Automated Flight Training System		0.3	Logicon

*Few of these systems have yet been procured

**Cost estimates, including acquisition, installation and spare parts for procuring ten visual systems over period 1979-1981. Memo UPT-IFS Visual Systems, AFSC, 7 March 1977.

cue (bank): the pilot feels a centrifugal force, head to seat, in the vertical plane of the aircraft. A simulator can accurately provide the initial rotary cue. However, because the simulator is fixed to the ground, sustained bank angle produces an erroneous cue; the pilot's tilted body is pulled to the ground rather than directly to the seat. "Washout" is the technique which reduces this erroneous cue. After the turn is initiated, the bank angle is restored to normal at a rate below the pilot's threshold of awareness; at the completion of the turn, the platform is rotated in the opposite direction, followed again by washout.

Koonce found that all groups trained in the simulator performed better in the aircraft, i.e., positive transfer of training as shown by fewer errors in the aircraft. However, the group trained without motion showed about the same performance in the air as did those trained with motion. This was the first study, as far as is known, to demonstrate that motion in flight simulators does not contribute more than no motion does in training pilots to fly aircraft. Many previous studies had shown, with some exceptions, that motion improved a pilot's ability to fly a simulator. (Puig 1970; Gundry 1976 a, b; Matheny, Lowes, and Bynum 1974; Huddleston 1966; Klier and Gage 1970; Muckler et al 1959; Borlace 1967; Brown, Johnson, and Magnall 1960). But the effect of simulator motion on aircraft performance had not been explored. In fact, Koonce's study was concerned not directly with motion but with determining the value of ground-based simulator performance measures for predicting pilot proficiency in aircraft.

Jacobs and Roscoe (1975) confirmed this finding in a further study which was described in Chapter V. Subjects trained in the Link GAT-2 with motion, including randomly reversed motion, showed no reliably greater transfer to the airplane than did those with no motion.

Starting in 1974, the Air Force undertook a series of studies to determine whether flight simulators used for training

need motion systems and reviewed plans to procure simulators which would include them. As of this writing (May 1977), some F-16 flight simulators will be procured without motion systems. However, it will be possible to add motion systems at a later time if it can be shown that they are cost-effective for training. A summary of current studies is shown in Table 16; some of the findings are based on briefings and informal discussions and are obviously subject to change; results of some of the studies were not available at the time of writing.

In every case, students trained in a simulator without motion performed as well in the air as students trained with motion. The presence of motion in the simulator does not seem to make a significantly observable contribution to flight performance. This applies to undergraduate and to graduate military pilots and, in Roscoe's studies, to qualified instrument pilots and to college students with no previous flight experience. It applies to the ASPT, T-4G, and Link GAT-2 simulators which have, respectively, motion systems with 6, 3, and 2 degrees-of-freedom. It applies to gentle maneuvers (take-off, straight-in, overhead traffic patterns) and to advanced undergraduate acrobatics (Immelman, Cuban 8, clover leaf, barrel roll). KC-135 pilots trained with motion were better able to handle outboard engine failure on takeoff than those trained without motion; this finding applies only to training in the simulator and was not tested in flight.

It has generally been accepted that fidelity of simulation is important for training purposes. To meet this need, motion systems have been improved with respect to mechanization, driving algorithms, response rates, and degrees-of-freedom. Nevertneless, motion in improved simulators does not contribute significantly to effectiveness of training, and it is difficult to believe that the findings can be modified substantially by additional studies.

TABLE 16. SUMMARY OF RECENT EXPERIMENTS SHOWING EFFECT OF SIMULATOR MOTION ON TRAINING

TASKS	SIMULATOR	AIRCRAFT	SUBJECTS	RESULTS	REFERENCE
Instrument flight	Link GAT-2 2 DOF[1] Bank and pitch	Piper Aztec	Instrument pilots 30 motion, sustained bank and pitch 30 motion, washout of bank in turns 30 no-motion	All groups benefitted from simulator; no-motion group benefitted most	Koonce (1974)
Initial Flight Training 11 maneuvers	Link GAT-2 2 DOF	Piper Cherokee Arrow	Flight-naive subjects 9 motion, washout 9 motion, random bank direction, washout 9 no-motion 9 aircraft only	All groups benefitted from simulation; no significant difference in aircraft between motion and no-motion groups (no subject aware of random, reversed motion	Jacobs and Roscoe (1975)
Air-to-surface weapons delivery (10^o, 15^o, 20^o)	ASPT (8 sorties) 6 DOF	F-5B (2 sorties)	UPT graduates 8 motion 8 no-motion 8 aircraft only no ASPT	No differences between simulator group in aircraft as measured by bombing scores and IP ratings, simulator trained pilots better (50%)	Briefing "ASPT: F-5B lead in training"[2]
Instrument Training	T-4G (3 DOF) T-4 (fixed base)	T-37	UPT students 8 motion 7 no-motion	No difference in flight hours required to reach proficiency	Woodruff and Smith (1974)

[1]Location of the center of pitch rotation behind the pilot's center of gravity creates the impression of vertical acceleration accompanying angular pitch accelerations.

[2]Topical Review on Vision and Motion Simulation, ODDR&E, 25 February 1977.

Continued

TABLE 16 (Continued)

TASKS	SIMULATOR	AIRCRAFT	SUBJECTS	RESULTS	REFERENCE
Contact Maneuvers: instrument, formation, navigation	ASUPT 6 DOF	T-37	UPT students 4 motion 4 no-motion	No differences in time in ASUPT and in T-37	Woodruff, Smith, Fuller and Weyer (1976)
Contact maneuvers: take-off, air work, straight-in, overhead traffic pattern	ASUPT 6 DOF	T-37	UPT students 4 motion 4 no-motion	No differences in aircraft	Briefing[2]
Basic and advanced contact maneuvers	ASPT 6 DOF	T-37	UPT students 8 motion 8 no-motion 8 aircraft only no ASPT	No differences in ASPT and in aircraft; simulator groups superior to control	Briefing "ASPT OUT"
Basic acrobatics: ASPT loop, aileron roll, split S, lazy 8. Advanced acrobatics: Immelman, Cuban 8, clover leaf, barrel roll	ASPT 6 DOF	T-37	UPT students 12 motion 12 no-motion 12 aircraft only no ASPT	Positive transfer of simulator to aircraft; no significant benefits from motion (study in progress)	Briefing "ASPT: motion - no-motion"

TABLE 16 (Continued)

TASKS	SIMULATOR	AIRCRAFT	SUBJECTS	RESULTS	REFERENCE
Take-off, overhead patterns, GCA, aileron rolls, slow flight	ASPT[3]	--	3 instructor pilots	Performance superior with no motion; reduced FOV degraded performance; G-seat improved performance with narrow FOV	Irish, Grunzke, Gray and Waters (1977)
Outboard engine failure on take-off	FSAA[4] (KC-135A) 6 DOF	--	36 SAC pilots qualified in KC-135 9 no motion, no visual 9 motion only 9 visual only 9 motion and vision	Pilots trained with motion and vision best; those trained with motion performed better than those trained without motion	DeBerg, McFarland and Showalter (1976)
Contact maneuvers: overhead pattern, GCS, loop, aileron roll, barrell roll	ASPT Motion: 0,3,6 DOF; Vision FOV: full, 144^0 H x 36^0 V, 48^0 H x 36^0 V; G-seat: on, seat pan only, off	--	5 Instructor pilots	Results not yet available	Briefing[2]

[3]Motion: 0; 3 DOF: pitch, roll, heave; 6 DOF
FOV: Full 240^0 H x +120 V, -40V; partial 48^0 H x 36^0 V
G-seat: On, seat pan only, off
Environment:
Turbulence: 0, light, moderate
Crosswind: 0, 12 kt, 24 kt
Ceiling/visibility: clear, minimums

[4]NASA Ames Flight Simulator for advanced aircraft
Redifon visual system (VFA-07) model board system, color TV, 48^0 H x 36^0 V

TABLE 16 (Continued)

TASKS	SIMULATOR	AIRCRAFT	SUBJECTS	RESULTS	REFERENCE
Air combat maneuvering	SAAC[5] Motion No-motion	F-4	--	Results not yet available	Briefing "SAAC air combat maneuvering training test"
Air-to-air	ASPT SAAC			Results not yet available	Briefing "ASPT/SAAC G-seat, G-suit training evaluation"
Basic flight control tasks	ASPT Motion: on-off Visual FOV: narrow-full	T-37	16 UPT students	Planned study	Briefing: "ASPT visual-motion interaction evaluation"
Air-to-air combat maneuvering	Northrop[6] Lamars 5 DOF	--	--	Study underway	Briefing: "Five DOF simulator ACM training effectiveness"

[5]Simulator for air-to-air combat at Luke AFB

[6]Large amplitude multimode aerospace research simulator

Nevertheless, it is important to observe strict qualifications to the findings based on the use of ASUPT in these studies. ASUPT, the Air Force's Advanced Simulator for Undergraduate Pilot Training at Williams Air Force Base, is a unique flight simulator. (It is now called ASPT, Advanced Simulator for Pilot Training.) Its use and the undergraduate pilots who served as subjects in these experiments may have influenced the current results in the following ways:

1. Wide-angle visual system

The visual system in ASUPT provides a wide angle, computer-generated image of the external visual world that is 240° horizontal and 160° vertical in size. This visual system, which was used in all experiments on ASUPT, creates an overwhelming impression of physical motion in the observer, even when the platform does not move. It can be noted in Table 16 that a reduced field of view led to some degradations in flight performance in the simulator; the effect of smaller fields-of-view in the simulator on performance in the aircraft will be determined in future studies.

2. T-37 Simulation

The ASUPT was configured to represent the T-37, a center-thrust, training aircraft. Engine-cut procedures were not tested in these experiments. Nevertheless, platform motion (i.e., yaw) might provide significant cues for training pilots in detecting asymmetrical thrust due to engine failure during takeoff in large multi-engine aircraft such as the KC-135. (DeBerg, McFarland, and Showalter, 1976)

3. The motion system in ASUPT

It is known that the motion system in ASUPT lags the visual system by about 100 ms. This is due to the fact that the update rate is 7.5 Hz for the motion system and 30 Hz for the visual system (Larsen and Terry, 1975). The ASUPT motion system will be improved so that its update rate is equal to that of the visual system.

4. Undergraduate pilots

The subjects in the ASUPT studies were undergraduate pilots and were flight-naive in the Jacobs and Roscoe (1975) study. Different results may be found with experienced pilots who would be more knowledgeable about motion cues in

the simulator. Ellis, Lowes et al (1967); Matheny, Lowes, and Bynum (1974); and Bergeron (1970) have shown that experienced pilots maintain about the same level of quality of performance in the simulator even when the fidelity of the motion simulation is varied for purposes of the experiment. However, the recent experiments did not examine the effect of such variations in simulator motion quality on performance in the aircraft. Further, the findings on the effect of motion fidelity on performance in the simulator may also be specific to the particular aircraft, maneuvers, and simulators used in these studies.

Thus, the finding that simulator motion does not contribute to aircraft performance has been demonstrated with some, but not with overwhelming generality: undergraduate pilots (with tests underway for more experienced pilots; simulators with a wide field-of-view (ASUPT) and no external visual display (GAT-2 in the Koonce and Jacobs studies); and center-thrust (ASUPT and T-37) and two-engine aircraft (GAT-2 and Piper Aztec), and on a simulator with a phase lag between the visual and motion systems (i.e., ASUPT). Additional studies are clearly needed, and some which are already scheduled are noted in Table 16. Issues which must be addressed include the quality of the motion simulation (in such critical aspects as the transfer functions, servo response, washout), ancillary cues (g-seat, g-suit, dynamic harness, and helmet straps), visual field of view (size and content of the imagery), compatibility between all cues provided in the simulator (particularly motion and vision), other types of aircraft (particularly motion and vision), other types of aircraft (particularly wide-bodied types), other military tasks and levels of pilot experience.

Although the findings appear to indicate that motion does not contribute significantly to training (under the conditions identified above), it would be a mistake to conclude that motion is not needed in all simulators or for all purposes for which flight simulators are or might be used. First of all, motion systems differ significantly in their response characteristics and degrees of freedom. This is shown clearly in Table 17, taken from Johnson,

SYSTEM / RESPONSE	SINGER (3 DOF)*	SINGER FB111 (5 DOF)	SINGER 48 INCH LEGS (6 DOF)	SINGER 60 INCH LEGS (6 DOF)	AMES FSAA	AMES (6 DOF)	NORTHROP LAMAR (5 DOF)	ATKINS & MERRIL (4 DOF)	ATKINS MERRIL (6 DOF)	REDIFO (6 DOF)
PITCH										
ROTATION (deg)	+14, -6	+14, -6	+26, -24	+30, -20	±18	±35	±25	+15, -10	+30, -20	±28
VELOCITY (deg/s)	12	12	15	15	29	97	60	10	22	17
ACCELERATION (deg/s²)	270	270	50	50	92	260	400	7100	90	80
FREQUENCY (Hz)**	0.5	0.5	1***	1***	1.5	0.55	3	0.7	1	0.7
ROLL										
ROTATION (deg)	±10	±10	±22	±22	±36	±35	±25	±10	±24	±19
VELOCITY (deg/s)	12	12	15	15	29	75	60	10	22	12
ACCELERATION (deg/s²)	270	270	50	50	92	570	460	7100	90	80
FREQUENCY (Hz)**	0.5	0.5	1***	1***	3.1	0.63	3	0.7	1	0.7
YAW	NONE									
ROTATION (deg)		±5	±29	±32	±24	±35	±25	±10	±35	±9
VELOCITY (deg/s)		–	15	15	29	170	60	10	22	11
ACCELERATION (deg/s²)		–	50	50	92	170	200	7100	90	80
FREQUENCY (Hz)**		–	1***	1***	1.7	0.7	3	0.7	1	0.7
VERTICAL										
TRANSLATION (ft)	±1	±1	+2.6, -1.9	+3.2, -2.5	±4	±9	±10	±0.5	+2.9, -3.5	±4
VELOCITY (ft/s)	–	–	2	2	6.9	7.5	13	0.33	2.1	2.5
ACCELERATION (G)	1	1	0.8	0.8	0.31	0.27	3	1	0.9	0.75
FREQUENCY (Hz)**	0.5	0.5	1***	1***	2.2	0.2	3	0.7	1	0.7
LATERAL	NONE							NONE		
TRANSLATION (ft)		±0.5	±3.5	±4	±40	±9	±10		±4.2	±6
VELOCITY (ft/s)		–	2	2	16	8	10		2.1	2.5
ACCELERATION (G)		–	0.6	0.6	0.31	0.29	2		0.7	0.7
FREQUENCY (Hz)**		–	1***	1***	1	0.54	3		1	1
LONGITUDINAL	NONE	NONE					NONE	NONE		
TRANSLATION (ft)			±4	+4.1, -4	±3	±9			+4.1, -4.5	±2.9
VELOCITY (ft/s)			2	2	5	9			2.1	2.5
ACCELERATION (G)			0.5	0.6	0.25	0.23			0.7	0.5
FREQUENCY (Hz)**			1***	1***	1.8	0.24			1	0.7
PAYLOAD										
WEIGHT (lb)	10,000	10,000	16,000	18,000	6,000	4,000	–	8,000	14,000	25,000
Ixx (SLUG/ft²)	–	–	33,000	33,000	–	–	–	–	–	–
Iyy (SLUG/ft²)	–	–	37,000	37,000	–	–	–	–	–	–
Izz (SLUG/ft²)	–	–	19,000	19,000	–	–	–	–	–	–

*DOF = DEGREE-OF-FREEDOM

**FREQUENCY AT 30° PHASE LAG

***ESTIMATED VALUE

†PAYLOAD CAN BE INCREASED TO 18 000 lbs

††COMBINED WITH LATERAL RADIUS OF 40 ft

TABLE 17. Typical Motion System Specifications. (Source: Johnson, Knight and Sugarman, 1975)

& L)	ATKINS MERRIL (6 DOF)	REDIFON (6 DOF)	REFLEC-TONE 60 INCH (6 DOF)	McDONNELL DOUGLAS (3 DOF)	McDONNELL DOUGLAS (4 DOF)	McDONNELL DOUGLAS (6 DOF)	CAE ELECTRONICS (4 DOF)	CAE ELECTRONICS (6 DOF)	CAE ELECTRONICS (6 DOF)
	+30, -20 22 90 1	±28 17 80 0.7	+30, -25 20.3 200 –	+15, -6 15 – –	+14, -9 20 25 –	±15 15 – –	+20, -12 10 50 –	±32 20 100 –	+32, -28 20 60 –
	±24 22 90 1	±19 12 80 0.7	±27 22.9 200 –	±10 20 – –	±15 – 5 –	±20 20 – –	±10 18 30 –	±28 20 100 –	±25 20 60 –
	±35 22 90 1	±9 11 80 0.7	±33 23.8 200 –	NONE	NONE	±10 10 – –	NO INDEPENDENT††	±34 20 100 –	±32 22 60 –
	+2.9, -3.5 2.1 0.9 1	±4 2.5 0.75 0.7	+3.2, -3.1 2.4 1.3 –	±1 1.7 0.5 –	±1 – +0.8, -1 –	±3 1 – –	+1.5, -0.5 0.9 0.3 –	±2.7 2 0.8 –	±2.8 2.8 0.75 –
	±4.2 2.1 0.7 1	±6 2.5 0.7 1	±3.6 2.9 1 –	NONE	±0.5 – – –	±5 3 – –	±5 3 0.1 –	±3.3 2.3 0.6 –	±4 3 0.5 –
	+4.1, -4.5 2.1 0.7 1	±2.9 2.5 0.5 0.7	+4.3, -3.5 2.7 1.1 –	NONE	NONE	±2 3 – –	NONE	±4 2.3 0.6 –	±4.1 2 0.5 –
	14,000 – – –	25,000 – – –	5,000† – – –	– – – –	– – – –	– – – –	– – – –	12,000 – – –	20,000 – – –

Knight, and Sugarman (1975). Note particularly the wide variations in acceleration and frequency. Other than noting the degrees of freedom of the simulator being used, very few studies report the dynamic response characteristic of the simulator being used. This information is needed in order to interpret and compare the results observed with various simulators. Further, for purpose of experimentation, it will also be important to be able to vary acceleration and frequency or, at least, to replicate experiments on simulators with different response characteristics.

Secondly, simulator motion may be needed for some types of training. Examples which come to mind include training for instrument flight where the pilot must be made aware of the fact that certain motion cues may mislead him and that instrument data are more reliable than what he may learn from the seat of his pants. A good list of instrument flight situations that may lead to incorrect judgments by the pilot may be found in Puig (1970, modified from a paper by Vinake, 1947). For example, a level turn may be interpreted as straight flight because the rate of change in turn is too small to stimulate the semicircular canals; straight and level flight maintained by successive corrections may be interpreted as gradual turning, due to cumulative effects on the endolymph. To demonstrate such effects, it may be desirable to vary the magnitude of various motion cues as well as to demonstrate them with full fidelity. DeBerg, McFarland, and Showalter (1976) have already shown that SAC KC-135A pilots trained with motion in a wide-body aircraft simulator, either with or without vision, can better handle outboard engine failure on takeoff than pilots trained without motion; tests were run only in the simulator. Other examples would include flight regimes in which the aircraft is marginally stable, e.g., stall, buffet, high angle of attack where motion cues may be noticed before visual ones. For all of the above instances where simulator motion would appear to be useful for training, it should be recognized that transfer of such

training, with or without motion, to the aircraft has not yet been tested or demonstrated.

The military services, particularly the Air Force, are conducting studies concerned directly with the need for motion in simulators. These studies address, in straightforward fashion, such significant issues as types of motion, field of view, pilot experience, flight task, and aircraft type (see Table 16). Attention is also being given to auxiliary motion cueing devices (e.g., g-seats, g-suits, shoulder straps) and to the interaction between motion cues (particularly vision and platform motion). The design of future studies should provide measures of transfer of training so that cost-effectiveness trade-offs could be made concerning the need for platform motion for particular types of training tasks and for training pilots at various levels of experience (e.g., undergraduates, transition training, continuation training). It may also become desirable, for experimental purposes, to be able to vary selected response characteristics of motion systems in order to identify those parameters which most influence transfer of training. These are thought to be angular velocity in the rotary planes and linear velocity and acceleration in the translation planes. Consideration should be given to modifying experimental flight simulators in order to make such tests possible.

B. Visual Systems

A flight simulator must show the outside visual world in order to be useful for training in such tasks as takeoff and landing, air-to-air combat, air-to-ground attack, carrier landing, and aerial refuelling. The content of the visual scene would obviously depend on the particular application, e.g., a landing field or aircraft carrier deck for takeoff and landing, a military installation or tanks with anti-aircraft weapons for air-to-ground attack, a tanker aircraft with a boom for aerial refuelling, and so on. The case of landing might be satisfied by a scene with limited detail, (e.g., runway shape, identification number, center stripes, threshold

and touchdown zone markings) and a field of view provided by a single CRT (e.g., 48° horizontal x 36° vertical). Air-to-ground attack might need much more detail (e.g., buildings, roads, vehicles, terrain features, ground-to-air defense weapons) and a wider field of view (the largest now available is 240° horizontal x 160° vertical). Various applications tend to favor a particular method of visual simulation and the characteristics of some typical display systems are shown in Table 18 (taken from Johnson, Knight, and Sugarman, 1975). Some of the characteristics shown in this table can be improved (e.g., McDonnell Douglas Corporation has announced a Vital TV system which adds twilight and day scenes to the previous night-only capability; General Electric has announced a capability for 2.7 arc minutes resolution, instead of 7 arc minutes, and more scenic detail for its Compu-Scene system) and rapid changes in the capability of visual simulations should be anticipated. As shown earlier, visual systems can add from \$0.3M to \$4.5M to the cost of a flight simulator. The smaller cost would provide a single-channel, narrow field-of-view, night-only scene, consisting entirely of light points; the higher cost provides scenic detail and a wide field of view for the pilot, such as in ASUPT. The visual system can easily be the most expensive component of a modern flight simulator and could account for 50 to 60 percent of the procurement cost.

Although visual systems are identified primarily by the data base used to store the imagery, e.g., model board, CGI or film, each system also requires some means for processing the data and presenting it for observation. A model-board system is based on a real, scaled-down world of miniature buildings, roads, and mountains; the pilot sees a portion of this as a function of how he maneuvers his aircraft. An optical probe and TV camera on a gantry moves over the model as if it were an airplane. Basic limitations of this system are that the maneuvering area is strictly limited by the size of the model board and pronounced optical distortion due to limited depth of view as the probe approaches

SYSTEM / SPECIFICATION	VITAL II VITAL III	REDIFON MODEL TYPE C1973 (AT AMES)	REDIFON MODEL TYPE C1965 (AT AMES)	REDIFON BELT TYPE C1967	SINGER NVS
FORMAT	SPOTS	MODEL	MODEL	MODEL	SPOTS
HUE	*LIMITED COLOR	–	COLOR	FULL COLOR	LIMITED COLOR
BRIGHTNESS (fL)	15	–	6*	18 (7.3' x 5.5' PICTURE)	–
RANGE	1000 mi	–	6 mi	3.8 x 4.5 mi	19.0 mi
RESOLUTION (arc min)	5	–	6	6	2
FIELD OF VIEW					
HORIZONTAL (deg)	44	–	46	48	46
VERTICAL (deg)	30	–	38	36	29
TIME OF DAY	NIGHT**	–	DAY-NIGHT	DAY, DUSK, NIGHT	NIGHT
ATMOSPHERE					
CEILING	0-10 kft - CLEAR	–	–	0-1750 ft	–
RUNWAY VISUAL RANGE	0-40 kft - CLEAR	–	–	300 ft - 27 kft	–
CLOUDS	0-40 kft - CLEAR	–	–	–	–
VIEWING POSITION	9 IN RADIUS	–	0.5 ft RADIUS	1 ft RADIUS*	9 in RADIUS
UPDATE RATE	30/s	–	30/s	–	30/s
GEOMETRIC DISTORTION	3% MAX	–	–	2.5% MAX	–
RESPONSE					
PITCH					
ROTATION (deg)	UNLIMITED	±25	+20, -30	±24.5	UNLIMITED
VELOCITY (deg/s)	UNLIMITED	140	170	29	UNLIMITED
ACCELERATION (deg/s^2)	UNLIMITED	1260	1250	57	UNLIMITED
FREQUENCY (Hz)	1.2	2.9	2.8	–	1.2
ROLL					
ROTATION (deg)	UNLIMITED	±180	±100	UNLIMITED	UNLIMITED
VELOCITY (deg/s)	UNLIMITED	310	290	86	UNLIMITED
ACCELERATION (deg/s^2)	UNLIMITED	5100	5200	200	UNLIMITED
FREQUENCY (Hz)	1.2	2.8	2.8	–	1.2*
YAW					
ROTATION (deg)	UNLIMITED	UNLIMITED	+70, 250	UNLIMITED†	UNLIMITED
VELOCITY (deg/s)	UNLIMITED	190	190	42	UNLIMITED
ACCELERATION (deg/s^2)	UNLIMITED	1700	1700	129	UNLIMITED
FREQUENCY (Hz)	1.2	2.9	2.8	–	1.2*
VERTICAL					
TRANSLATION (ft)	UNLIMITED	0.006, 4 (12 ft, 8 kft)	0.014, 1.25 (28 ft, 2500 ft)	0.006, 0.875 (12, 1750 ft)	UNLIMITED
VELOCITY (ft/s)	UNLIMITED	1.4 (168,000 ft)	0.093 (11,000 ft/min)	0.034 (4,000 ft/min)	UNLIMITED
ACCELERATION (ft/s^2)	UNLIMITED	1.8 (110 G)	0.24 (15G)	0.064 (4G)	UNLIMITED
FREQUENCY (Hz)	1.2	.32	0.75	–	1.2*
LATERAL					
TRANSLATION	1000 mi	+7.5 ft (±15 kft)	±4.5 ft (±9 kft)	±4 ft (±8 kft)††	190 mi
VELOCITY (ft/s)	UNLIMITED	0.9 (M1.6)	0.5 (M.91)	0.21 (M.39)	UNLIMITED
ACCELERATION (ft/s^2)	UNLIMITED	1 (62G)	0.45 (28G)	0.032 (2G)	UNLIMITED
FREQUENCY (Hz)	1.2	2.9	0.42	–	1.2*
LONGITUDINAL					
TRANSLATION	1000 mi	+32 ft (±64 kft)	±17.5 ft (±35 kft)	38 ft (76 kft)	190 mi
VELOCITY (ft/s)	UNLIMITED	0.68 (M1.2)	0.53 (M.96)	0.15 (M.27)	UNLIMITED
ACCELERATION (ft/s^2)	UNLIMITED	1 (62G)	0.80 (50G)	0.016 (1G)	UNLIMITED
FREQUENCY (Hz) AT (30° PHASE LAG)	1.2	2.8	0.52	–	1.2*
SCALE	–	1:2000	1:2000	1:2000	–

* ESTIMATED VALUE

** SEE SEC. 2.2.2.4 (I) FOR DISTINCTIONS BETWEEN VITAL II AND III

† AT ±60° CLOUDS SWITCHED IN

†† MODEL 10 ft WIDE

TABLE 18. Typical Visual Display Systems Specifications. (Source: Johnson, Knignt and Sugarman, 1975)

SINGER NVS	SAAC SINGER FARRAND	ASUPT GE-FARRAND	GE 2F90	GE LAB SYSTEM	SINGER VAMP	SINGER MARK V MODEL TYPE
SPOTS	MODEL + STYLIZED	STYLIZED	STYLIZED	STYLIZED	FILM	MODEL
LIMITED COLOR	MONOCHROME	MONOCHROME	FULL COLOR	FULL COLOR	FULL COLOR	FULL COLOR
–	6	6	2.5	2.5	20	5
19.0 mi	UNLIMITED	–	60 mi	–	UNLIMITED	5.2 x 14.5 nmi
2	1	7	11	7	3	3
					48	48
46	200	240	180	30	36	36
29	+120, 30	+120, -40	60	23	DAY, DUSK, NIGHT	DAY, DUST, NIGHT
NIGHT	DAY	DAY-NIGHT	DAY	DAY	ELECTRONIC	–
					O-CLEAR	O-CLEAR
–	–	CONTROLLED	–	–	O-CLEAR	O-CLEAR
–	–	VARIABLE FOG	VARIABLE FOG	VARIABLE FOG	O-CLEAR	O-CLEAR
–	DISTANT	TEMPORARY	–	–	9 in RADIUS	9 in RADIUS
9 in RADIUS	1 ft RADIUS*	0.5 ft RADIUS	2 ft RADIUS	9 in RADIUS	–	–
30/s	30/s	30/s	30/s	30/s	DEPENDS ON AIRCRAFT POSITION*	–
–	–	–	–	–		
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	±18°	UNLIMITED
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
1.2	1.2	0.8	1.2	0.8	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	– –
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
1.2°	1.2°	0.8°	1.2°	0.8°	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	±25°	UNLIMITED EXCEPT AT EDGE
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
1.2°	1.2°	0.8°	1.2°	0.8°	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	±1° FROM GS*	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
1.2°	1.2°	0.8°	1.2°	0.8°	–	–
190 mi	UNLIMITED	–	60 mi	–	±10° FROM LOC*	±8 ft (16 kft)
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
1.2°	1.2°	0.8°	1.2°	0.8°	–	–
190 mi	UNLIMITED	–	80 mi	–	APPROACH	±22 ft (44 kft)
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–	–
UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	UNLIMITED	–	–
1.2°	1.2°	0.8°	1.2°	0.8°	–	–
–	–	–	–	–		1:2000

the surface. Since the maneuvering area is limited to an equivalent of about 5 by 15 miles, pilots soon become familiar with the terrain, which may reduce the value of such simulation for training for air-to-ground attack, although not necessarily for landing.

A CGI (computer-generated imagery) system stores scenic content in digital form and calculates visual perspective for each television frame based on the instantaneous eye-point position and orientation of the aircraft in three-dimensional space. The gaming area can be large (200 x 200 miles in one current device), moving objects can be shown, scenic detail is flexible, and the system has a great ability to follow aircraft position and attitude in space. However, scenic content is abstract and the surfaces and objects lack texture. The display is degraded by flashing or streaking of the image when the velocity limitations of the system are exceeded. A CGI with a wide angle field of view produces a compelling impression of movement through space. It is reported that highly experienced pilots do not notice when platform motion is turned off during a demonstration flight on a simulator with a wide angle CGI system, but this finding has not been tested systematically.

Although many model board systems remain in use, they will probably be replaced by the CGI systems which are more flexible and cost about the same amount. However, there is only one known study which compares the transfer of training from such systems to aircraft; when used for landing training on the KC-135, a CGI and a night-only display showed slightly more transfer than a model board, but the differences were not significant (J. Thorpe 1977 unpublished). All current visual systems have some advantages and deficiencies. Some film systems are still in use, but it is difficult to believe that new ones will be procured. Here, the basic data consist of photographed images, on 70-mm film, of some flight path, typically an approach and landing. Deviations from the normal flight path are produced in the simulator for moving the optical system. Such systems have good resolution and brightness

and are less expensive than the other storage mechanisms noted here; however, they have very limited maneuvering flexibility from the normal flight path and their use would, at best, be limited to approach and landing. Many combinations of data storage, processing, and display are feasible; the advantages and disadvantages of various combinations have been reviewed by Bliss (1969); Driskell (1974); Johnson, Knight, and Sugarman (1975); the Committee on Vision of the National Academy of Sciences (1975); and Lewis (1970).

Visual systems are demonstrably more costly than motion systems and the utility of flight simulators will depend critically on their contribution to a wide variety of training tasks. The RDT&E program on visual simulators is directed primarily towards improving the technology of storage, processing, and display of visual data. A summary of expenditures for visual simulation for FY 1977 is shown in Table 19; the particular projects are identified in Appendix C. An interesting fact is that industry spent $3.2M in FY 1976 (the last year for which such data were available) for Independent Research and Development on various aspects of visual simulation, obviously related to the anticipated procurement of flight simulators with visual systems. Excluding IR&D, the total budgeted for visual simulation in FY 1977 is $16.3M; about 60 percent for the Air Force alone. Major efforts include the development of the Army Laser Scan Visual System, the Navy Aviation Wide Angle Visual System (AWAVS), and the Air Force's Electro-Optical Viewing System.

The development of visual displays for flight simulators is driven strongly by what can be done and not particularly by what is needed in a display to make it cost-effective for training purposes. About 85 percent of the funds shown in Table 19 are allocated for Advanced and Engineering Development. Projects for FY 1977 and FY 1978 which may contribute to clarifying visual requirements for flight simulators are listed in Table 20. Almost

TABLE 19. SUMMARY OF DOD RDT&E PROGRAMS ON VISUAL SIMULATION, FY 1977 (PROJECTS IDENTIFIED IN APPENDIX C)

		FY77
ARMY		
6.2	Exploratory Development	$ 340K
6.3	Advanced Development	882
		$1222K
NAVY		
6.2	Exploratory Development	1124
6.3	Advanced Development	3575
6.4	Engineering Development	447
		$5146K
AIR FORCE		
6.1	Research	40
6.2	Exploratory Development	800
6.3	Advanced Development	1385
6.4	Engineering Development	7700
		$9925K
	TOTAL DOD	$16,293K
IR&D (FY 1976)		$3205K

TABLE 20. PROJECTS CONCERNED WITH VISUAL REQUIREMENTS FOR FLIGHT SIMULATION, FY 1977 and FY 1978

ARMY

PE 62727A

A230-02 Visual display technology

Laser generated visual displays.
Development and specification of requirements for a flight training research simulator.
Suitability of day computer generated imagery for flight simulators in navigation training.
Terrain model board and SFTS requirements (AF-1Q weapons system simulator)

NAVY

PE 62757N

F-55-525/6711 Standards for visual systems

PE 63720N

4781 Aviation Wide-Angle Visual System

AIR FORCE

PE 61102F

2313 Visual motion cue analysis

PE 62205F

1123 Comparison of CGI, model board and night only displays for KC-135A pilots
ASPT runway touchdown zone visual requirements
ASD/SD-24 area of interest display evaluation
TAC A-10 training research program
T-4G visual display parameter evaluation
ASPT visual/motion interaction evaluations (vary FOV)
Army display performance test

6114 Evaluate area of interest display for air crew training
Determine CIG sensor simulation fidelity requirements

all of these studies are concerned with the transfer of training of particular, existing visual simulation systems. The size of the field of view is being varied in some of the ASUPT studies concerned with the need for platform motion discussed previously. AWAVS will be used, in an off-line mode, to prepare imagery which can be used in studies of visual fidelity.

Unpublished research results show no significant differences in landing the KC-135 for pilots trained in B-707 simulators with motion and different wide angle display systems, i.e., day color CIG (Boeing), day TV-model board (American Airlines), or a night calligraphic system (American Airlines); Thorpe (1977). Some technical options in visual systems will be evaluated: e.g., area-of-interest (high-resolution inset), real vs virtual image display, and improved use of edges in CGI data processing. Most papers presented at the 1977 Image Conference (Williams AFB, 17-18 May 1977) were concerned with equipment, but some research results were also reported. Kraft, Anderson, and Elworth (1977) showed that point sources used currently to indicate runway lights in a CGI night scene gave pilots the impression that they were higher on a glide slope than when these sources were attenuated in luminous intensity to compensate for atmospheric attenuation and for excessive depicted size. Crawford, Topmiller, and Ritchie (1977) reported that subjects tend to overestimate distances under "clear" and "reduced visibility" conditions in a CGI display, although experienced crew members are more accurate than naive subjects; the tests involved slant ranges of about 0.6 to 7 miles on a screen with a field of view of $18.5^{\circ}V \times 22.5^{\circ}H$. Overestimation was reduced, but still present, when more detail (called "texture") was added in the experiment. A literature review by Ritchie (1976) attempts to evaluate information from experiments on visual perception, the history of art, and techniques used in motion picture animation and, thereby, to suggest approaches to research to improve computer-generated displays. However, there appears to be neither a systematic program nor a plan to develop the test

facilities which would be needed to identify the required perceptual characteristics of visual displays (e.g., resolution, surface texture, modelling of objects, color) in order to establish specifications for such devices and to determine the areas of technology which need greatest support, based on criteria of maximum contribution to required image quality, feasibility, cost, technical risk, and the time required for development. There is a deficit in our research literature on the minimal and necessary characteristics of visual systems for simulation. The pilot will probably want the real world, even though there is evidence that he can land his airplane if we provide him with as little as three dots of light properly oriented on the ground (Flexman). There seems little reason to build systems with the highest possible fidelity without knowledge of whether or not they are needed. Related to the urgent need for development of visual systems is an equally pressing need to develop simulations of other sensory systems such as radar images, IR displays, LLLTV displays, and possibly of electronic countermeasures. The research budget for visual simulation appears to be $40K (Air Force 6.1).

R&D on visual simulation needs a focus that is not apparent in the current budget of $16M. It is important to distinguish between what may be seen in a visual display and the mechanisms that are used to generate that display. The pilot sees what is in the display and presumably is not much concerned with how it got there. Visual displays do not have very high fidelity; there is, as yet, no method of visual simulation in which the observer cannot tell the difference between a real object and that shown in a visual display. This is quite different from auditory simulation where, for example, an observer cannot distinguish between a musical group and a sound system, provided both are behind a curtain.

Many of the technologies currently available to store, process, and display a visual scene are shown in Figure 7. The performance requirements for a visual flight simulator are identified, <u>without</u>

DATA BASE

- CGI
- Model Boards
- Photographic
  - Straight
  - Multiplexed
- Holography
- Video Disc
- Digital
- Environment
  - Weather
  - Visibility
  - Time of Day
  - Shadowing
- Scenic Detail
  - Terrain
- Weapons and Effects
- Vehicles
- Aircraft
- Surface Objects

INPUT DEVICE

- Core/Disc Complex
- Scanner/ Detectors
- Optical Probes

PROCESSING

- CGI
- Channel Multi- plexing
- Data Base Multiplexing
- Areas of Interest
- Insetting

OUTPUT

- Scanned
  - Laser
  - TV
- Unscanned
  - Photographic
  - CRT Line Drawing
- Plasma
- Display Mechanism
  - Real, Virtual
  - Visual Dome
  - Screen
  - CRT
  - Projection
  - Helmet

VISUAL SCENE

- Resolution
- FOV
- Color
- Brightness
- Objects, Motion
- Texture
- Maneuver Area
- Exit Pupil
- Compatibility with Non-Visual Cues
- Delay
- Refresh Rate
- Dynamic Character- istics

FIGURE 7. Technologies used to generate a visual display of the external world (modified from a chart used by J. Harvey, NTEC, at a topical review, 17 Feb 1977)

quantitative values, on the right. These values have not been established and, in recent systems, reflect what can be done rather than what is needed. An R&D program on visual simulation is needed to establish performance requirements. Basically, this involves determining the transfer effectiveness, from simulator to aircraft, of training with simulations of scenes that differ in such major visual parameters as resolution, field of view, surface texture and scenic content. The order of priority for these studies should approximately follow, in decreasing order, the cost of the subsystems needed to provide these visual characteristics. Since the ASUPT and AWAVS simulators were designed to be used for experiments in training, some of these visual studies could be conducted at these facilities. Little effort has been made to examine in detail the flexibility or the availability of these devices for studies of visual requirements. It may well be that the use of other visual devices, or the development of new ones, may be needed for an effective research program on visual simulation. There also exists a large body of literature and highly qualified scientific expertise in visual perception which may help focus an experimental program designed fundamentally to establish the visual requirements for visual displays in flight simulators. Information concerned with visual thresholds, e.g., size, contrast, and brightness, is well established and there are good models which predict detection, recognition, and identification of objects. It is believed, however that little systematic work has been done on such critical matters pertaining to visual simulation as field of view, surface texture, scenic content, and the amount of detail required within objects; the interested reader is referred to Gibson (1966), Graham (1965), and Kaufman (1974), among others. There is no recognized measure of visual fidelity. Measures of image quality are widely used in the design and evaluation of photographic and television systems, e.g., modulation transfer function, intensity transfer function, and granularity or noise. (See Shade, Biberman 1973). Measures of image quality are concerned with the ability of an imaging system

to duplicate the real world, and not with the structure and content of visual scenes.

Provisional visual requirements can be derived initially from the visual specifications for ASUPT and AWAVS modified, to the extent that information exists, to improve known limitations of these systems, and to meet standards based on the visual research literature. Then, the technologies listed in Figure 7 should be reviewed to identify those areas where improvements appear feasible, either to improve visual characteristics and/or to reduce costs. The main factors to be assessed appear to be technical feasibility and risk, development time, cost, the availability of qualified organizations to perform the work, and the compatibility of the development's schedules with those for the anticipated procurement of simulators which could incorporate these visual devices. The training value of such potential improvements is largely unknown. The military services have, of course, coordinated their R&D programs in the sense that the Air Force has supported the development of wide angle virtual image displays, the Navy has supported wide angle real image displays, and the Army has supported laser displays. However, it is believed that a coordinated plan for research on visual simulation technology and on visual perception as suggested above, does not exist at present and is needed to provide guidelines and priorities for future efforts This is regarded as crucial because of the high relative cost of visual displays in flight simulators and of their major significance for training purposes.

VI. DISCUSSION

Increased dependence on flight simulators for military flight training was mandated primarily by guidance from DoD that the services should reduce total flying hours. The policy was the result of congressional pressure related to the "high cost" of flying. If present plans to procure simulators are followed, it is estimated that the use of simulators will permit a reduction of total flying hours by 14 percent in FY 1978 and by 17 percent in FY 1981. Thus, while flight simulators may save money by reducing flying hours, it is also necessary to demonstrate that they are effective for training purposes. If the use of simulators is extended to operational training, it will become necessary to demonstrate that their use does not reduce operational readiness. Pilots cannot be expected to favor reduced flying hours particularly if, in their opinion, it may interfere with combat readiness.

Operating costs per hour of current simulators are about 5 to 20 percent those of comparable aircraft. This suggests that simulators could be more cost-effective than aircraft for training, provided that simulator time to reach a specified level of performance on a flight task does not exceed aircraft time for the same purpose by the reciprocal of the values shown above, i.e., by not more than about 20 to 5 times. Considerable transfer of training data from older simulators (and a few modern ones) to aircraft are well within this limit and they strongly imply that simulators should be cost-effective. The amount of transfer is not constant but should be expected to vary with such factors as the task, the rate of usage per pilot, the experience level of the pilot, the particular type of simulator, and the instructional strategy employed in the training

program. However, the conclusion that flight simulators are cost-effective relates effectiveness with old simulators and generally unspecified instructional strategies with current operating cost data for simulators and aircraft. Given improved training curricula and advanced simulators with improved instructional facilities and improved fidelity, there is compelling reason to expect similar or greater cost-benefits in the future without loss of training effectiveness. This remains to be demonstrated, since few of the advanced simulators are in actual use. In three current cases, it appears that the procurement cost of a flight simulator can be amortized within periods of 0.75 to 2 years, as found by an airline, the Navy (P-3C), and the Coast Guard (HH-52A and HH-3F). In these cases, flight performance was found to be the same as or superior to that observed before simulators were used in training. From these studies, it is not possible to separate the contributions of the simulators and of the improved training curricula to the observed levels of performance. Projections submitted to Congress by the DoD suggest that the median amortization period for 97 units of 24 types of simulators will be 4.8 years. Clearly, the length of the amortization period depends not only on the effectiveness of the simulator as a training device (e.g., flight hours saved) but also on the rate of utilization and on various assumptions upon which the cost estimates are based.

All current estimates of savings due to the use of flight simulators are based on the amount of flight time saved after training pilots on some portion of the curriculum, either in the simulator or in the aircraft. This procedure provides a conservative estimate of savings because it overlooks a well-known fact about training, namely that the learning curve has an asymptotic shape. Additional training improves performance by diminishing increments. Thus, it becomes important to determine the marginal productivity of flight simulators for various types of tasks. There is a cross-over determined by comparing the Incremental Transfer Effectiveness Ratio of the simulator to the simulator/aircraft

operating cost ratio, after which additional training in the simulator is no longer cost-effective. Determination of the Incremental Transfer Effectiveness Ratio for this purpose requires an experimental design in which one of the variables is amount of time spent in the simulator. This appears to have been accomplished only by Povenmire and Roscoe (1973) for the GAT-1 simulator, and Jacobs and Roscoe (1975) for the GAT-2 simulator, both for training student pilots. The need for such studies is recognized and studies are scheduled by the Air Force for FY 1979 and later. These should consider not only how the rate of improvement changes in the simulator but in the aircraft as well.

Most or all of the data describing the "effectiveness" part of the cost/effectiveness ratio was derived from transfer of training-type studies where the criterion is savings in flight time. A realistic perspective on simulator effectiveness requires that other dimensions be considered as well. For example, training on the flight simulators used by the Coast Guard at Mobile, Alabama, may have contributed to saving two aircraft that had inflight failures. In the past, i.e., prior to flight simulator training on the specific emergency, aircraft were lost when flight failure occurred. The dollar savings that occurred because of the successful outcome of these two emergencies is supposedly more than the initial cost of the entire training facility. The fact that we cannot conduct controlled experiments in this area of benefits does not mean that the increments in safety attributable to flight simulators are not important.

Other measures of simulator training effectiveness that should receive attention might include the following:

a. Level of skill and procedural ability retention achieved via flight simulator training versus aircraft training.
b. The adaptive capacity of the pilot to react to situational exigencies.
c. The effect on the pilot's workload potential.

d. The effect on the reliability and consistency of the pilot's performance.

e. The effect on the pilot's sensory responsiveness and vigilance as well as judgment in decision making.

f. The effect on the pilot's self-confidence and acceptance of the training.

The fact that we do not have adequate measures of the dimensions of effectiveness only emphasizes our need for a more thorough and comprehensive structuring of simulation research.

Representative values for the procurement cost of current flight simulators are shown in Table 21. These vary from $1.1M for the T-34C instrument flight simulator to $24.0M for the B-1 mission flight simulator. It is conceivable that the procurement cost of a modern simulator may approach, or perhaps exceed, the procurement cost of an airplane. That, in itself, is not an argument against use of the simulator because the simulator may still be more cost-effective on a life-cycle basis for specific types of training than the airplane. We have already shown that the simulator has a favorable operating cost and that there is extensive evidence that performance learned in the simulator transfers to the airplane and saves flight time. A factor that favors the simulator and, of course, contributes to the lower operating cost (to the extent that fixed costs are significant), is that it can be used many more hours per year than an airplane. Utilization for a simulator can exceed 5000 hours per year (18 hrs per day x 6 days a week x 50 weeks per year = 5400 hours) while military aircraft utilization is in the range of about 500 hours per year, according to the estimates shown in Table 22. On economic grounds alone, it is likely that, over their life cycles, flight simulators will remain less expensive to own and operate than aircraft. Obviously, the other critical issue is whether flight simulators are effective for training, so that the cost-effectiveness of simulators and aircraft for training can be directly evaluated.

TABLE 21. REPRESENTATIVE PROCUREMENT COSTS FOR FLIGHT SIMULATORS. (SOURCE: DoD REPORT ON FLIGHT SIMULATION, 1977)

Simulator	Procurement Period (FY)	No. Procured	Average Cost
Army			
UH-1 Synthetic Flight Training System	76-78	12	$ 3.3M
CH-47 Synthetic Flight Training System	79	2	8.2
AH-1 Synthetic Flight Training System	79	3	10.9
UTTAS Synthetic Flight Training System	79	2	7.2
Navy			
A-6 Night Carrier Landing Trainer	77-78	2	7.9
CH-53 Operational Flight Trainer	77	1	4.9
EA-6B Part Task Trainer	77	1	5.4
E-2C Part Task Trainer	78	1	1.3
P-3C Operational Flight Trainer	78	1	6.5[1]
S-3A Weapon System Trainer	76	1	
T-34C Flight Instrument Trainer	78	10	1.1
F-18 Trainer	79	1	23.1
Air Force			
A-10 Training Flight Simulators	76	2	6.6
Instrument Flight Simulators	77-78	10	5.1
B-1 Mission Flight Simulators	78-79	3	24.0
C-5 Cockpit Procedure Trainers/ Nav.	77	3	3.7
C-130 Cockpit Procedure Trainers	76	2	3.9
Mission Simulators	77-78	5	6.3
C-141 Cockpit Procedure Trainers	77	7	1.3
F-15 Instrument Flight Trainers	76-78	7	4.0
F-16 Training Flight Simulators	78	4	9.5
F-111 Mission Simulator	77	1	9.9
T-37/38 Instrument Flight Simulators	76-78	18	3.4

[1]A value of $4.2M is used in Browning, Ryan, Scott and Smode (1977) p.76.

TABLE 22. PROJECTED AVERAGE ANNUAL FLYING HOURS PER AIRCRAFT ACCORDING TO MISSION, FY 1981

Mission	Regular Navy	Regular Air Force
Undergraduate flight training	574 hrs	602 hrs
Transition/training	430	303
Mission/not industrially funded	422	323
Mission/industrially funded	-	861
Support flying	485	503
Average, all missions	457 hrs	430 hrs

Source: Navy Aircraft Program Data File, Jan. 1977 (Secret)
USAF Program, Aerospace Vehicles and Flying Hours, Vol. I, by M/D/S, PA FY-78-POM, 7 May 1976 (Secret)

Cost data needed to evaluate the cost-effectiveness of alternative training programs are not now being collected in a systematic and comparable fashion useful for trade-off studies between simulators and aircraft (Baron, 1974). This is particularly the case for comparing the training programs of different services.

The data reporting systems that do exist are generally limited to extracting full costs of given training programs from base accounting systems for the purpose of setting reimbursement rates for inter-service or foreign student training. Except in the area of flying-hour costs, there is no attempt in such systems to associate or correlate types and levels of resources consumed with increments in training loads or with the particular activities within training programs. The development of such data entails costs, and one would anticipate that, in the absence of specific requirements and models for estimating training costs, necessary data would be found lacking. There are large areas of commonality in resource requirements between flight training and other facets of peacetime military operations. In these common areas the applicable data can be considered available. However, there remain significant resource-consuming activities that are peculiar to the training establishment for which requisite data have not been developed. This is especially true in the area of training equipment costs (including flight simulators) and direct instructional and instructional support personnel requirements.

On the basis of these findings, the present investigation turned to the particular costs attributable to flight training. (See Vol. II) Basic considerations surrounding the role of flight simulators (and extendable to considerations of other training equipments and resources) were developed from traditional economic analysis. A model was formulated that emphasizes analyses of cost trade-offs between flight and flight simulation. A result of this formulation is to identify the general types of data that

would be required for its implementation, and the availability of these types of data has been investigated for each of the three services. The model is neither sufficiently detailed nor complete to serve as an analytical tool. Rather, it provides a guide for further development of analytical methods and data collection systems by the military services in order to assess the cost impacts of proposed training program changes.

Deficiencies in the data base limit the ability of the services to estimate cost impacts of flight training simulators. There is also a need for training effectiveness data in order to assess net values of program alternatives, including substitution of simulation for other modes of training and evaluations of alternative simulator configurations. Development of an adequate data base is a first order of business, since methods and analytical models that might be developed are useful only to the extent that they are consistent with the form in which data can be developed.

The services are using different strategies to procure flight simulators. The Army is following a step-by-step approach while the Air Force is planning a series of large-scale procurements. Each type of strategy carries a risk. Should simulators prove to be cost-effective, cost savings would be lost by the Army approach. If they do not, especially in the area of use for training on skill maintenance, the Air Force program would result in a large investment in devices that do not fully serve their intended purposes. Judging which type of program is more appropriate is beyond the scope of this paper.

It is clear from many studies conducted since about 1950 that flight simulators are effective training devices. No attempt was made to review the earlier studies in detail, because they were conducted on simulators that have long been obsolete and used training procedures that are unclear or difficult to reconstruct. Many recent and relevant studies are available for examination. Measures of transfer of training were evaluated or calculated

where the required data were available in 20 studies concerned with the effectiveness of flight simulators conducted over the period of 1967 to 1977. The crucial aspect in all of these studies is not whether a pilot can improve his performance in a simulator but the extent to which skills learned in a simulator can be transferred to an aircraft. There is a consistent finding in these studies that skills learned in a simulator carry over to the aircraft. The median TER is 0.45, which may be taken to be the fraction of time spent in the simulator which carries over as time saved in the aircraft, compared to a control group which was trained only in the aircraft. In fact, the TER's vary from almost 0 to 0.9. Clearly, it would be important to identify the factors which lead to small or large amounts of transfer and this can be accomplished only by a systematic and coordinated research program. An attempt to interpret the different amounts of transfer found in the studies presently available is not warranted due to limited information about the flight curricula, tasks, and performance characteristics of the simulators that were used. Thus, R&D is needed to establish the actual TER's for various tasks and training curricula on currently available simulators. If time in the simulator is included as a variable (i.e., several experimental groups with different amounts of time in the simulator), it will be possible to approximate the shape of the learning curve and the point at which the simulator reaches its marginal utility as a training device. That information is needed to relate incremental training effectiveness to cost of training and the basis on which to determine when simulators and aircraft can each be used on a cost-effective basis.

Most modern flight simulators possess sophisticated capabilities for instructing pilots and measuring their performance. These include, for example, the ability to insert predetermined conditions which, if uncorrected, lead to malfunctions during flight; to freeze flight conditions, or to replay maneuvers for purpose . review, or to repeat a maneuver from some convenient starting

point; to demonstrate automatically certain maneuvers or preferred procedures; and to score pilot performance and to provide the student with diagnostic information concerning his performance.

One of the main considerations in the design of ASUPT, when it was conceived in 1967, was to provide facilities for research concerned with such issues as performance measurement and instructional strategies in undergraduate pilot training. Our ability to establish the effectiveness of alternative ways of training will be no more accurate than our ability to measure the performance of pilots in simulators and in aircraft. Recent reviews of this topic may be found in Rusis, Spring and Atkinson (1971), Koonce (1974), and Waag et al (1975). Almost all of the data cited in this report to demonstrate the effectiveness of flight simulators are based on subjective ratings of pilot performance in simulators and in aircraft. Much previous research has been devoted to objective measurement of pilot performance, but the current method still uses instructor pilots to judge whether students have performed various maneuvers within specified tolerance limits. Given proper training, such judgments have a high reliability, i.e., correlations of about 0.7 to 0.8 on repeated measurements between rides and between observers. Objective and automated performance measurements have been used in many studies in simulators and aircraft, but the judgment of Instructor Pilots is still the basic means of evaluating pilot performance in routine flight training. All services conduct research on performance measurement of pilots and aircrew. However, this topic should receive greater priority, considering the contribution that objective performance measures could make to answer many questions about the optimum utilization of flight simulations.

It cannot escape notice that the effective development and use of flight simulators for training purposes is influenced by factors other than RDT&E, the major concern of this paper. The limited use of simulators in the past was not a dominant issue as long as sufficient funds were available for military flying.

Obvious limitations in the performance of flight simulators and a low regard for their training value both contributed to their low usage and to the lack of support for their improvement. Interest of the airlines provided the initial impetus towards the improvement of flight simulators over the last 10 years, and additional support came from Congress and the DoD as a consequence of the oil embargo and of budget pressure to reduce military flying. Still, user acceptance will ultimately determine whether the military services can realize the potential savings and efficiencies afforded by the use of flight simulators. Strong direction and support at top levels in the services and the DoD will be required to influence an effective use of simulators.

Despite their large aggregate expense, no procurement of flight simulation equipment is large enough to meet the criteria of a DSARC review. The Defense Systems Acquisition Review Council (DSARC) reviews systems programs having an anticipated cost of $75 million in research, development, test, and evaluation or $300 million in production (DoD Directives 5000.1, January 18, 1977; 5000.2, January 18, 1977; 5000.26, January 21, 1975). The training system is a relatively minor item in the procurement cost of an aircraft which does not meet these criteria; the aircraft, of course, does. The training system does not appear to receive major attention. Yet, the life-cycle cost impact of a particular type of flight simulator may be large when it is procured with (or without) such features as, for example, motion platform, wide angle visual system, or instructional and performance scoring capabilities. The findings in this paper suggest that little valid data are yet available on the cost-effectiveness of current flight simulators, and this applies especially to the cost-effectiveness of their major components. Flight simulators are procured typically as part of the aircraft weapon system development under the control of the program manager. However, they may also be procured by separate funding if they are developed after the aircraft system has been acquired, e.g., the B-52 flight

simulator. The key issue is to make sure that the design and procurement of flight simulators are evaluated in terms of their impact on life-cycle costs, whether at DSARC or otherwise. However, the management issues which would have to be resolved in order to implement such a policy were beyond the scope of this study.

An increased use of flight simulators would appear to be supportable on the basis of their cost-effectiveness for undergraduate, transition, and continuation training. The limits to this argument are not apparent at the moment. Thus, it is legitimate to be concerned with the extent to which the savings possible by substituting training in flight simulators for aircraft, particularly in the case of continuation training, might lead to undesirable consequences for combat readiness. Some minimum amount of flying aircraft appears necessary to exercise the systems which would support military combat flying, such as logistics, maintenance, servicing, protection, repair, transportation, and command and control. Total system capability, as well as flight skills, must be maintained, and it would be a narrow view of flight training which disregarded this contribution to military readiness. A program which would attempt to establish the minimum necessary amount of flying appears just as important as one to determine the most cost-effective use of flight simulators.

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APPENDIX A

VARIABLE OPERATING COSTS OF SOME SIMULATORS AND AIRCRAFT, FY 1975 AND FY 1976

NOTE: These data summarized in Volume 1, Chapter 2, Table 4

Description		Operating cost per hour Simulator	Aircraft	Cost Ratio Simulator/ Aircraft	Reference
Air Force					
B-52D	Flight Trainer	$ 86	$2801	-	AFR 173-10[1]
	Elect. Warfare	65			
	Bomb/Nav.	51			
	Gunnery	24			
B-52G	Flight Trainer	71	2841	-	"
	Elect. Warfare	74			
	Bomb/Nav.	67			
	Gunnery	26			
B-52H	Flight Trainer	73	2630	-	"
	Elect. Warfare	77			
	Bomb/Nav.	68			
	Gunnery	26			
FB-111	Weapon System	193	1951	-	"
	Bomb/Nav.	238			
	Egress	229			
SR-71	Weapon System	181	-	-	"
KC-135	Flight Simulator	70	1595	0.04	"
F-4C	Weapon System	158	1277	0.12	"
F-4D	Weapon System	120	1255	0.10	"
F-4E	Weapon System	88	1220	0.07	"
RF-4C	Weapon System	81	1092	0.07	"
F-111A	Flight System	179	2240	0.08	"
F-111D	Flight System	100	2240	0.04	"
F-111E	Flight System	184	2240	0.08	"
F-111F	Flight System	93	2240	0.04	"
F-106	Mission Trainer	114	1014	0.11	"
A-7D	Weapon System	82	1024	0.08	"
C-5A/B	Flight Simulator	100	3610	0.03	"
C-141	Flight Simulator	93	1272	0.07	"

Description	Operating cost per hour Simulator	Aircraft	Cost Ratio Simulator/ Aircraft	Reference
Air Force Continued				
C-130E Flight Simulator	97	638	0.15	AFR 173-10
C-135 Flight Trainer	169	1090	0.16	"
CH-3 Flight Simulator	109	352	0.31	"
HH-53 Flight Simulator	109	579	0.19	"
T-37 (T4) Flight Simulator	9	224[2]	0.02	"
T-38 (T-7/T-26 Flight Simulator	10	518[2]	0.02	"
Army				
UH-1 Flight Simulator	38	190[3]	0.02	Directorate of Cost Analysis, Comptroller of the Army, December 1976
CH-47C Flight Simulator	94	858	0.11	"
AH-1Q[2] Flight Simulator	69	234	0.29	"
CH-54 Flight Simulator	-	1393	-	"
CH-6 Flight Simulator	-	63	-	"
DH-58 Flight Simulator	-	67	-	"
TH-55 Flight Simulator	-	66	-	"
Navy				
S-3A Flight Simulator	200	501	0.40	Aircraft Program Data File, Jan. 1977
F-4 (Navy) Flight Simulator	-	1169	-	"
P-3C 2F69D Flight Simulator	134	602	0.22	"
2F87F Flight Simulator	144	602	0.24	"
Coast Guard				
HH 52A VCTS	59[4]	504[4]	0.12	Isley et al 1974
HH 3F VCTS	59[4]	815[4]	0.07	"

Description	Operating cost per hour Simulator	Aircraft	Cost ratio Simulator/ Aircraft	Reference
Airlines				
B-707 Flight Simulator	$ 213[5]	$ 935	0.23	Civil Aeronautics Board (1976)[6]
B-737 Flight Simulator	140	599	0.23	"
B-727 Flight Simulator	140	735	0.19	"
B-747 Flight Simulator	275[5]	2358	0.12	"
DC-8 Flight Simulator	150	1107	0.14	"
DC-10 Flight Simulator	175	1341	0.13	"

[1]USAF Cost and Planning Factors, 173-10, 20 January 1977

[2]Includes base maintenance labor

[3]Reimbursement rate for U.S. government agencies

[4]Assumes 75 percent utilization of simulator, 12 hr x 5 days x 48 weeks

[5]Average of 3 simulators

[6]Operating expenses per block hour, (excluding crew), trunk airlines, domestic operations, 1975; simulator cost data from private sources.

APPENDIX B

SUMMARY OF STUDIES WHICH EVALUATE THE EFFECTIVENESS OF FLIGHT SIMULATORS FOR VARIOUS TYPES OF TRAINING, 1939-1977*

*NOTE: This appendix is based largely, but not entirely, on summaries which appear in papers by Carter (1971), Micheli (1972) and Diehl and Ryan (1977). Some of the studies cited in these papers were not available for review. Studies are identified in References.

TABLE B-1. SUMMARY OF STUDIES ON THE EFFECTIVENESS OF FLIGHT SIMULATORS

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Mahler and Bennett (1949) review					
NRC, 1939	Civilian light aircraft	Link AN-T-18	Basic contact flight for civilian pilot training program.	Analysis of performance records (N=10). No control group.	Estimate that 5 to 7 hrs. in trainer was equivalent to 3 hrs in A/C. Savings of 2 to 4 hrs air time. (Inconclusive)
NRC, 1940	Civilian light aircraft	Link AN-T-18	Basic contact flight for civilian pilot training program.	Analysis of performance records (N=10). No control group.	Estimated 2½ hrs saving in air time with 6 hrs of trainer time. (Inconclusive)
NRC, 1941	Civilian light aircraft	Link AN-T-18	Basic contact flight for civilian pilot training program.	Instructor performance ratings. Three groups of 14, 8, and 11 civilian pilot training students.	Groups with more Link trainer time were rated higher than group with only one hour of training. (Inconclusive)
Naval Reserve Aviation Base, Long Beach, CA 1942	Military	Link	Basic flight training.	(N=146) No control group.	(1) Reduced number of dual instruction hrs for solo. (2) Reduced number of students receiving downs on their check flights. (Inconclusive)
Naval Flight Preparatory School, William Jewell College, Liberty, Missouri 1943	Military	Contact Link	Basic flight training.	(N=1400) 1/2 received 10 one hr sessions on Contact Link Trainer. Other ½ no synthetic training.	Experimental students tended to slight advantage over control students in capability for solo time, actual solo time, and instructor's grades. (Differences were not statistically significant.)

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Naval Air Station, Memphis 1945	Military	12BK-1 Primary Landing Trainer	Primary training	(N=166) 1/2 experimental and 1/2 control.	(1) Experimental students completed syllabus faster than controls by 16%. (2) Control group had 10% more flight failures in A stage, 5% more in B stage. (3) Differences disappear by end of C stage.
Univ. of Illinois, 1949	SNJ	(1) 12-BK-1 Landing Trainer (2) C-3 Cycloramic Link Trainer (3) SNJ Cycloramic (General) Link (1-CA-2)	Instrument training and control skills	(1) experienced S's (solo flight time) (N=234) (2) 10 hrs syn. trainer (N=465) (3) Control group (N=427)	Three trainers equivalent: accidents reduced 40%; failure rate down 33%
Williams and Flexman (1949)	SNJ-5 Modified for civilian use	SNJ Cycloramic Link (1-CA-2)	Basic contact flight training	(2 groups of 6 college students ea. 12 hr flt syllabus.) Trainer group: 8 hrs on trainer. Control group: 11 hrs A/C.	12 hrs to learn in air; 5 hrs air time for trainer group. Fewer errors for trainer group.
Mahler and Bennett (1950)	PBM (2-engine seaplane) PB4Y (4-engine land plane)	PBM-OFT PB4Y-OFT	Familiarization and instrument training.	Series of controlled experiments using 23 matched prs. of students for each trainer.	Flight time reduced 1½ hrs. out of 12 hr syllabus for INST; no saving for FAM stage. Fewer errors in both stages.

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Brown, Matheny and Flexman (1950)	SNJ	School Link with "blackboard" runway.	Ground reference maneuvers (landings. forced landings, pylon 8's)	N=20 college students 10 on trainer 10 principles training	Trainer group = 2.59 errors Control group = 4.29 errors
Wilcoxon, Davy and Webster (1954)	SNJ	SNJ OFT (Specialized electronic high fidelity trainer) and NavBIT (General low fidelity basic instrument and radio range trainer)	Instr. training including radio range.	Progress-at-own-rate syllabus and ground training under a blocked sequence Std. Blk Syl NavBit N=96 OFT N=33 Exp. Black Syl N=168 N=52	(1) saved an av. of 1.3 hrs in flight or > 3000 hrs/hr or, 1 flight out of 11 bas. inst. flts. (2) NavBit equal in effectiveness to SNJ OFT for basic instrument training and slightly superior for radio range work.

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Flexman, Towsend and Ornstein (1954)	T-6 (Navy SNJ)	P-1 (1-CA-2 SNJ Cycloramic Link)	Procedures; maneuvering	95 aviation cadets; 47 in trainer. Substituted 40 simul. hrs for 30 flt hrs in a 130 hr syllabus	40 sim. hrs = 30 flt hrs ratio = 0.75
Payne, Doherty, Hasler et al (1954)	SNJ	Cycloramic Link	Approach and Landing	Experimental group (N=6) vs control group (N=6).	61% fewer trials & 74% fewer errors for simulator group.
Dougherty, Houston and Nicklas (1957)	SNJ	Cycloramic Link, photo-mockup, procedures trainer	Procedures	3 trainer groups compared to each other and flight group.	All groups equal after three air trials.
Isley, Caro and Jolley (1968)	Army Helicopter	1-CA-1 modified to rotary-wing configuration.	Instrument flight in rotary wing training. (U.S. Army Aviation School)	Total N=145, 3 groups: 0 hrs, 10 hr, and 20 hr synthetic training. All groups received 25 hrs flight training.	No significant difference between groups.
Caro, Isley and Jolley (1968)	Army Helicopter	"Whirlymite" captive helicopter	Rotary wing contact flight.	Total N=132. Divided into 2 experimental groups and 2 control groups with no training on device. 0, 3¼, 7¼ hrs of practice.	(1) 10% attrition for flying deficiencies in exper. groups. 30% attrition for control groups. (2) Two hrs less flight training needed to solo for exper. groups. (3) Flight grades higher early in training.

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Crook (1967)	light aircraft	ground trainer	private pilot course. instrument flight		16 sim. hrs reduce flight from 42 to 35 hrs. 17 sim. hrs reduce flight from 40 to 21 hrs.
TWA (1969)	B707	B707	Flight procedures		
Houston (1970)	B727 BAC 400	B727 BAC 400	Flight procedures Flight procedures		
Caro, Isley and Jolley (1973)	T-42	GAT-2	transition and instrument qual.		Increase from 21 hrs in old sim. to 25 hrs in new sim reduced flight from 60 to 35 hrs.
Caro (1972)	UH-1 helicopter	2B24	Instrument flight		43 sim hrs reduce flight from 60 to 7 hrs.
Browning, Ryan and Scott (1973)	P-3	2F69	four engine turboprop transition course		increase from 11 to 14 sim hrs reduced flight from 19 to 12 hrs.
O'Connor and Glennon (1973)	TA-4	2F90	Basic instrument and navigation		revised course increases sim from 21 to 27 hrs and reduces flight from 35 to 19 hrs

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Povenmire and Roscoe (1971)	Piper Cherokee	(1) AN-T-18 (Link "Blue Box") (2) GAT-1	Flight course leading to private pilot certificate.	52 students in four groups: (A) previous flt trng; (B) A/C; (C) AN-T-18; and (D) GAT-1	Grp. / Av.Flt. Hrs. to Crit. / Tnr Hrs / Sav. Flt Hrs / Trans. Effec. Ratio A/C 45.5 AN-T-18 36.5 11 9 0.8 GAT-1 34.5 11 11 1.0
Meister, Sullivan, Thompson and Finley (1971)	S-2E aircraft (4-place, twin engine, carrier-based ASW aircraft	2F66A WST	Weapons system training. Both team and individual trng for air anti-submarine warfare missions.	To demonstrate learning through measured performance improvement. Subjects: VS-41, San Diego N=13, VS-30, Key West, N=12. (Same subjects performed in different operator positions on different sessions.)	(1) #4 Oper. (Julie-Jezebel) showed substantial learning. #3 (MAD, ECM, radar and Nav. Computer) and TACCO showed minor improvement. (2) San Diego students gained more than Key West students (Difference resulting from location). (3) More frequently used as individual than team trainer. (When first used as team trainer, performance decreases, then improves.) (4) Instructor evaluations of trainer (via questionnaire) - criticism of equipment. Reliability and lack of realism of A/C simulation inputs. San Diego instructors rated device highly; Key West instructors did not.

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Robins and Finley (1972)	P-3A	2F69B (P-3A Weapon System Trainer)	Air ASW Tactics	Practice in trainer; then transfer to flight.	Improved on the trainer; in-flight transfer data analysis not yet completed.
Ryan, Puig, Micheli and Clarke (1972)	TA-4J	2F90 (TA-4J Operational Flight Trainer)	Basic Instrument Flight	Groups: (1) Control (standard training) (2) Flight only (3) Simulator only (4) Academic only 30-33 subjects per group	No difference on flight check between flight and trainer groups. Simulator group saved 4 flight hours (55%) (1)
Woodruff, Smith and Morris (1974)	T-37	T-4G	Contact flight		15 sim hrs reduce flight from 27 to 23 hrs
	"	"	Undergraduate instrument flight		Revised course reduces sim hrs from 23 to 15 and flight from 21 to 10 hrs.

(1) Report says "The substitution of trainer time for time on the operational equipment is an excellent way of increasing cost-effectiveness" (p.1) but no cost data are provided.

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Isley, Corley and Caro (1974)	H-52 helicopter	VCTS	Search and rescue qualifications		22 sim hrs reduce flight from 78 to 36 hrs
	"	"	search and rescue transition		18 sim hrs reduce flight from 31 to 28 hrs
	H-3 helicopter	"	" " "		30 sim hrs reduce flight from 36 to 23 hrs
A/S Rescue and Recovery Service (1974)	H-3 helicopter	T-42	Transition to search and rescue		19 sim hrs reduce flight from 63 to 37 hrs.
Woodruff, Smith, Fuller and Weyer (1976)	T-37	ASUPT	Basic jet course		Revised course increases sim from 17 to 60 hrs and reduces flight from 91 to 71 hrs
Brown (1976) Brown (1975)	B-747	B-747	Transition training		sim. 28-19; a/c 6-2
	B-707	B-707	" "		27-19 13-1+
	B-727	B-727	" "		28-19 12-1+
	DC-10	DC-10	" "		23-19 2-2
Diehl and Ryan, (1977) p.21	E-2	2F65	2 engine turboprop transition course		15 sim hrs (compared to none) increased flight from 61 to 68 hrs

TABLE B-1 (Continued)

Study	Vehicle	Simulator	Skills Taught	Experiment	Results
Browning, Ryan, Scott and Smode (1977)	P-3	2F87F 2F69D	four engine turboprop transition course for ASW	27 pilots trained on 2F87F and P-3C and new curriculum compared to 16 trained on 2F69D and P-3C on old curriculum	increase from 9 hrs in old sim to 24 hrs in new sim reduces flight from 15 to 9 hrs.
Eddowes (1977)	T-37	ASPT	Undergraduate maneuvers		
	T-37	T-4G	contact flight		
	T-37	T-4G	instrument flight		
	T-37	T-4	" "		
Diehl and Ryar, p.22 (1977)	C-130	T-19	transition to 4 eng. turboprop		increase in sim from 30 to 32 hrs reduced flight from 23 to 18 hrs
" "	C-141	T-37A	" " "		40 sim hrs (from none) reduced flight from 17 to 15 hrs

APPENDIX C

RDT&E PROJECTS OF THE MILITARY SERVICES ON VISUAL SIMULATION, FY 1977 AND OF INDUSTRY (IR&D), FY 1976

ARMY		FY77
62727A		
A230-02	Visual Display technology Wide angle laser scan 360° annular visual system Optical image display Visual simulation analysis	$ 340
63209A		
DB-39	Flight simulation components CGI computational technology Digital processing of imagery	$ 882

NAVY

62757N

		FY77
F-55-522	Training NTEC	
F-55-525	Human Engineering. NTEC, NADC, PMTC, NAMRL, NWC	
4751	Cost effective simulation in flight training	$100
4742	Computer generated visual displays for training	125
3714	Forward looking infrared simulation in Naval training devices	45
3718	Holography for carrier landing	47
4744	Generalized VTOL simulation mathematical model	45
5714	TV projection system	40
5742	Flight simulation system test technology	14
6711	Standards for visual systems	33
7711	Holographic displays for training devices	30
6714	Laser air to ground and air to air weapon delivery systems	50
3719	Optical memory for sensor simulation	60
5741	Simulation computing techniques	115
6716	Holographic memory for training applications	38
6718	Advanced sensor simulation utilizing charge coupled devices	62
6722	High resolution CCTV multiple target insertion for Nav. tng. devices	53
6724	Solid state image sensors	7
7714	Multiple image display system for periscope navigation	50
7716	Optical systems for training device development	30
7719	360^{o} non-programmed visual display	150
7715	Lasers for training device development	30
		$1124

63720N

WPN 09	Training devices technology. NTEC	
4781	Aviation wide angle visual system (AWAVS)	$3575

64703N

SPN 47	Laser and holographic applications	$ 447

AIR FORCE

	FY77
61102F	
2313 Human resources. OSR	
Visual motion cue analysis	$ 40
62205F	
6114 Simulation techniques for AF training	
CIG image improvement	$ 62
High res. color projector	45
Multiviewer display	63
Multiviewer display	58
CIG edge utilization	75
Schlieren display	75
Sensor characterization	50
Sensor data base	70
Sensory modeling	119
IOS display evaluation	70
Simulation software	60
Simulator testing	53
	$ 800
63227F	
1958 Training simulator technology integration. AFHRL-FT	
Holographic monochrome visual display	$ 625
Holographic color visual display	150
High resolution color camera	30
High resolution liquid crystal projector	100
Wide angle multiviewer	--
Advanced sensor simulation system	350
Alternate sensor implementations	--
	$ 1255
2364 Advanced CIG visual/sensor system (plus $25K in-house)	$ 130

AIR FORCE Continued

64227F Flight simulator development. SIM. SPO

		FY77
2201	KC-135 Boom operator trainer	$ 800
	B-52 Aerial refueling trainer	2700
2269	Electro-optical viewing system (EVS)	1700
2322	Multi-crew visual systems, wide field of view (MCVW)	
	-01 Low cost wide angle display	600
	-02 Low cost, high resolution, wide angle image generator	400
	-03 Requirements verification	500
2360	Tactical air/ground simulations (TAGS) A-10	1000
		$7700

DEFENSE AGENCIES[1]		FY77
IR&D		
Flying Training Technology		
0509-76DL	Air Combat visual simulation Goodyear Asrosp. Corp.	$ 450
7048	Advanced Tactical fighter simulation. McDonnell Douglas/ McDonnell Acft Co.	224
		$ 674
Simulation technology for training		
76005401	Digital visual hardware development. Image Gen. Corp. Singer	$ 100
76005402	Digital visual software studies scene content. Singer	200
76005414	Development of high resolution color monitor Singer	80
76005444	Wide angle display system eval. Singer	200
75005433	Wide angle digital image gen. display. Singer	--
76005405	Advanced simul. tech. software systems. Singer	425
76005432	Calligraphic-digital gen. visual system. Singer	24
*76005445	Laser camera system study. Singer	15
76D5C53	CGI system technology. General Electric	225
76D5C55	Electro-optical viewing system sim. GE	60
*76D5C57	High resolution digital radar landmass simulation. GE	350
*7047.01	Development of adv. simulation concepts. McDonnell Douglas	321

*Same figures also used for training devices

[1]Note: All data on IR&D taken from "FY 78-82 Research and Technology Plan, Part III, Air Force Human Resources Laboratory, 15 August 1976. Data apply to FY 1976.

DEFENSE AGENCIES Continued FY77

Simulation technology for training, cont'd

74R102	Area of interest display technology for GCI. GE	$ 44
74R103	GCI terrain presentation. GE/ Valley Forge Space Center	43
75RC04	Advanced GCI architecture. GE/ Valley Forge Space Center	55
74R105	Advanced GCI data base technology. GE/Valley Forge Space Center	9
5001.01	Visual simulation technology studies. McDonnell Douglas Corp. Electronics Co.	300
60604002	IR&LLTV simulation study. Honeywell, Inc./Marine Systems Div.	80
		$2531